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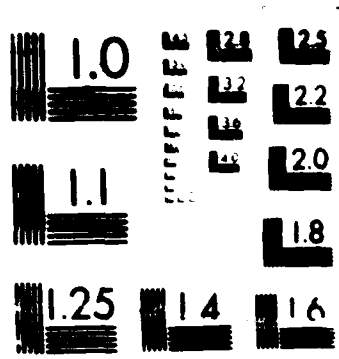

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FUEL PROPERTY EFFECTS ON THE COLD STARTABILITY OF NAVY HIGH-SPEED DIESEL ENGINES

INTERIM REPORT
BFLRF No. 207

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Four Navy high-speed diesel engines were tested for startability at 5°C. The engines were the Detroit Diesel Allison 4-53T, Detroit Diesel Allison 4-71TI, Cummins NH-220, and Westerbeke 4-108. Initially, starting time versus temperature curves were determined for each engine using a MIL-F-16884H base fuel. Next, starting times at 5°C were determined for progressively lower ignition quality fuels. The test fuels were obtained by mixing progressively larger volumes of three low-cetane fuels with the base fuel. Multiple linear regression analysis was performed using the cranking speed and fuel properties as the independent variables with starting time as the dependent variable. This yielded an equation for each engine that predicts starting time based on fuel properties and cranking speed.

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SUMMARY

In this program, four Navy high-speed diesel engines were tested for startability at 5°C. The engines were the Detroit Diesel Allison 4-53T, Detroit Diesel Allison 4-71TI, Cummins NH-220, and Westerbeke 4-108. Initially, starting time versus temperature curves were determined for each engine using a MIL-F-16884H base fuel. Next, starting times at 5°C were determined for progressively lower ignition quality fuels. The test fuels were obtained by mixing progressively larger volumes of three low-cetane fuels with the base fuel. Multiple linear regression analysis was performed using the cranking speed and fuel properties as the independent variables with starting time as the dependent variable. This yielded an equation for each engine that predicts starting time based on fuel properties and cranking speed.

FOREWORD

This work was conducted at the Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, TX, and at the Naval Ship System Engineering Station (NAVSSES) located at the Philadelphia Naval Shipyard, Philadelphia, PA. The work was funded by the David Taylor Naval Ship Research and Development Center (DTNSRDC), Annapolis, MD and the U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA. The work was conducted under Contract No. DAAK70-85-C-0007 during the period November 1983 through December 1985. Mr. F.W. Schaekel (STRBE-VF) served as the contracting officer's representative and Mr. M.E. LePera, Chief of Fuel and Lubricants Division (STRBE-VF) as the project technical monitor.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance provided by the BFLRF and NAVSSES technical and laboratory staff in the performance of the work and the BFLRF technical publications group in the preparation of this report.

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I. BACKGROUND

The Navy's preferred fuel for fossil-fueled surface ship power systems is a middle-distillate fuel conforming to the requirements of MIL-F-16884H Fuel, Naval Distillate (NATO F-76), which superseded MIL-F-16884G Fuel Oil, Diesel, Marine (DFM).(1-2)* This single "multipurpose" fuel is fired in boilers, diesels, and gas turbines. It was selected as the result of a conversion program conducted during the early 1970's that first converted all ships (except the AVM 1 and AR 6) burning a heavy blended fuel, MIL-F-859E Navy Special Fuel Oil (NSFO (NATO F-77)), to middle distillate, MIL-F-24397 Navy Distillate (ND).(3-4) A subsequent program converted all these ships to F-76, a slightly lighter and cleaner fuel than ND.

The decision to convert was made on the following basis:

- With the introduction of the gas turbine powerplant, conversion of the steam ships to a fuel that gas turbines could use would reduce the number of fuels within the Navy's surface fleet logistic system from three to two (a ship's propulsion fuel and an aviation fuel).

- Converting the steam-propelled ships from NSFO (NATO F-77) to a distillate would improve readiness by reducing or eliminating the problems associated with burning heavier fuels.

The decision to convert was economically feasible in the late 1960's because the reduced logistics burden and overhaul and maintenance costs more than compensated for the incremental increase in cost associated with using a distillate fuel in a steam propulsion system.

Since that conversion, however, Navy ships have had difficulty at times in obtaining F-76, or its predecessor DFM, in sufficient quantity and have had to use approved substitutes [e.g., JP-5 (NATO F-44) aviation fuel].(5) The supply problem can be especially acute outside the continental United States, and it has occasionally been

* Underscored numbers in parentheses refer to the list of references at the end of this report.

necessary to accept commercial diesel fuel that has not been fully qualified under the MIL-F-16884H requirement. Still, the most likely source of fuels for use by the Navy in the event of F-76 shortages is the Marine fuels marketplace.

With regard to the worldwide petroleum situation, there is a trend toward decreasing crude oil quality.(6) Light sweet crudes are easier and less costly to extract and process than heavier sour crudes and have been used preferentially in the past. As a result, reserves of lighter sweet crudes have diminished, and heavier sour crudes are traded more frequently today.(7)

While the quality of crude oil has been decreasing, the demand for the light and middle-distillate portions of the refinery product produced from the crude oil has been increasing. Since the refinery must match the product slate with that demanded by the consumer, it must produce more light and middle-distillate products than have been produced in the past from less and lower quality crudes. Therefore, the refiner must increase the use of conversion processes, including thermal and catalytic cracking of crude oils. As a result, the nature of the refinery product has been changing.

The F-76 specification was developed during an era of highly available light sweet crudes and the refinery processing techniques that are in use today were not taken into account during the specification development. Consequently, even though the Navy has been tightening the specification requirements for F-76 over the last decade, there have been more incidences of poorer quality specification fuel. This has been evidenced by the following:

- Increasing requests for purchasing waivers for certain fuel properties which are just "off-spec."
- Increasing awareness of specification fuels degrading in storage.

Also, data analyses of samples of fuel delivered to the Navy over the same period of time indicate a consistent trend among individual fuel properties toward the limits established in the F-76 specification.(8)

Therefore, the U.S. Navy's Shipboard Mobility Fuels Research and Development (MFRD) Program is being developed by the Energy Research and Development Office of the David Taylor Naval Ship Research and Development Center (DTNSRDC) to prepare for the reduced availability and quality of F-76 petroleum-based fuels and their possible replacement, in part, by alternates such as shale-oil and tar-sand-derived fuels. The goal is to develop the rationale and guidance for altering the Navy fuel specification (MIL-F-16884H) such that the availability of fuel to the Navy is significantly increased for both continuous and emergency use. As part of this rationale, a protocol will be established based on the minimum level of testing required to qualify a nonspecification fuel for shipboard use. The fuels addressed are those petroleum-derived (existing and future) or nonpetroleum-derived (future) fuels that do not meet the current Navy specification.

The MFRD Program takes into account all existing shipboard combustion equipment (high- and medium-speed diesel engines, gas turbine engines, and steam boilers) and fuel-handling equipment. The equipment groups to be tested initially will be the high-speed diesel engines, the gas turbine engines, and the fuel-handling equipment because they are believed to be the most sensitive to the expected deviations in properties relative to fuels that meet the current specification.

This report discusses the high-speed diesel engine evaluations sponsored by the Navy, and concentrates specifically on the cold startability of representative Navy engines with nonspecification fuels. The overall topical areas being evaluated under the high-speed diesel engine program are as follows:

- Diesel engine fuel injection studies
- Diesel engine performance evaluations
- Cold startability determinations
- Durability evaluations
- Thermal stability studies

The David Taylor Naval Ship Research and Development Center sponsored this work at two locations: The Belvoir Fuels and Lubricants Research Facility located at Southwest Research Institute (BFLRF/SwRI) and the Naval Ship Systems Engineering Station (NAVSSES) located at the Philadelphia Naval Shipyard.

II. SCOPE

Based on the population of high-speed diesel engines in the Navy's inventory (TABLE 1), the four engines that were included in this program were the Detroit Diesel Allison (DDA) 4-53T and 4-71TI engines, the Westerbeke/Perkins/Chrysler 4-107/108 engine (Westerbeke 4-108), and the Cummins NH-220 engine.(9) The injection and combustion systems on these engines are representative of approximately 94 percent of all Navy high-speed diesel engines (TABLE 1). The DDA 4-53T engine was chosen in addition to the 4-71TI engine due to the piston geometry in the 53-series engine. The 53-series engine uses a trunk-style piston, while the 71 series engine uses a crosshead-style piston. The DDA 4-71TI engine was included due to its high population in the Navy's fleet.

TABLE 1. Navy High-Speed Diesel Engines

Engine Type	Total Population, Units
DDA 71 Series	1088
DDA 149 Series	130
DDA 53 Series	129
Waukesha L1616DSIN	21
Waukesha L161DN	2
Hercules DFXD	23
Cummins NH-220	23
Cummins VA3000M	2
MTU 8V331TC80	12
Buda 6LD468	2
Westerbeke 4-107/108*	351
Gray 4D129	7
Gray 6D427	6

* Westerbeke 4-107 uses a wet cylinder liner while the 4-108 uses a dry cylinder liner.

The DDA 4-53T and the Cummins NH-220 engine tests were conducted at the Belvoir Fuels and Lubricants Research Facility/SwRI (BFLRF) at San Antonio, TX, while the

Westerbeke 4-108 and the DDA 4-71TI engine tests were performed at the Naval Ship Systems Engineering Station (NAVSSES) at Philadelphia, PA.

The base fuel for this work was a MIL-F-16884H Fuel, Naval Distillate (NATO F-76), henceforth referred to as F-76, which was procured and supplied by the Navy. The blending components required to vary the fuel properties were procured and supplied by BFLRF. The blending components and their properties are listed in TABLE 2.

Each of the three blending components shown in TABLE 2 (G, Q, and R) is a low-cetane material that, unless blended with a higher cetane fuel, will not allow the engine to start at 5°C. In addition to different cetane numbers, each of the three blending components has different viscosities, volatilities, and hydrocarbon types. These low cetane blending components were blended with the base fuel (A in TABLE 2) to form the test fuels.

The lubricant used in this work was a 30-grade MIL-L-9000G qualified product procured by BFLRF.(10) This lubricant was selected as being representative of the lubricants currently in use by the surface fleet.

TABLE 2. COLD START BLENDING COMPONENTS

Property	ASTM Method	A Base Fuel	G Heavy Aromatic Naphtha	Q High Aromatic LCO	R Xylene Bottoms
Specific Gravity at 15.6°C	D 1298	0.849	0.903	0.956	0.875
API Gravity, °API	D 287	35.2	25.5	16.5	30.2
Flash Point, °C	D 93	77	64.4	85.0	40.6
Cloud Point, °C	D 2500	-13	-18	+16	-5
Pour Point, °C	D 97	-17	<-50	-17	<-50
K. Vis at 40°C, m^2/sec	D 445	2.75 X 10^{-6}	1.43 X 10^{-6}	2.97 X 10^{-6}	0.75 X 10^{-6}
K. Vis at 5°C, m^2/sec	D 445	6.65 X 10^{-6}	2.78 X 10^{-6}	8.44 X 10^{-6}	1.17 X 10^{-6}
Distillation, °C	D 2887				
IBP		133.2	138.1	143.0	138.8
10%		208.9	184.1	233.3	143.7
20%		229.5	197.7	251.6	163.1
30%		245.7	207.6	261.9	163.1
40%		259.0	214.8	274.1	165.1
50%		273.4	225.0	285.1	167.8
60%		287.2	234.6	298.1	170.6
70%		303.8	242.0	313.1	173.3
80%		322.0	254.6	332.5	175.4
90%		346.0	265.5	353.1	183.4
99.5%		400.5	304.6	411.3	293.0
Distillation, °C	D 86				
IBP		191.7	182.2	194.4	150.0
10%		222.2	196.7	241.1	154.4
20%		235.6	202.8	252.2	155.6
30%		244.4	208.3	260.0	156.7
40%		253.3	213.3	267.8	157.8
50%		262.2	218.8	275.6	158.9
60%		273.3	225.0	283.3	160.0
70%		286.7	231.1	295.6	161.1
80%		302.8	238.9	311.1	163.3
90%		322.2	250.6	334.4	166.7
95%		338.9	259.4	352.8	171.7
End Point		348.3	275.0	367.2	218.9
% Recovered		98.5	99.0	99.0	99.5
Residue, vol%		1.5	1.0	1.0	0.5
Loss, vol%		0.0	0.0	0.0	0.0
Cetane Number	D 613	48.7	16.0	20.5	10.2
Aniline Point, °C	D 611	66.1	-26	8	-26
Aromatics, vol%	D 1319	26.3	89.1	76.1	100
Autoignition Temp, °C	E 659	189	301	323	362

III. PREPARATIONS FOR TEST

Since two of the engines were to be run at NAVSSES and two were to be run at BFLRF, close coordination between the two facilities was necessary. The test protocol was carefully reviewed by all concerned in order to assure test uniformity. Fuel blending components were shared by the two facilities, with chemical and physical property determinations performed by BFLRF. Weekly telephone conversations between NAVSSES and BFLRF personnel aided in coordinating the efforts of the two facilities.

Each engine was first rebuilt according to the respective manufacturers' rebuild specifications. The engine specifications and rebuild parts used in this program are listed in Appendix E. New parts used included pistons, liners, rings, bearings, and gaskets. Each engine was broken in according to the manufacturers' recommended break-in schedule shown in TABLE 3. The engines were then installed in refrigerated boxes to simulate cold-starting conditions. Fig. 1 shows the Cummins NH-220 engine installed in a cold box. Each engine was instrumented with calibrated thermocouples located to measure inlet air temperature (equivalent to the air temperature in the cold box), oil sump temperature, engine airbox temperature (DDA engines only), exhaust gas temperature, and fuel temperature. A fuel supply resting on a scale was used to measure fuel consumed during each starting attempt. Fig. 2 illustrates the fuel supply setup.

The engine coolant systems were filled with a 50/50 volumetric blend of ethylene glycol based antifreeze and potable water. The engine thermostats were blocked open, and the engine-mounted water pump was plumbed to circulate water through the engine.

The original design of the test plan called for using the startability requirement found in MIL-E-24455.(11) The specification calls for a cold soak at 1.7°C and an engine start within 10 seconds of cranking. Initial testing using the base fuel and electric starters revealed that none of the engines would start in less than 10 seconds. Because of this, the 10-second cranking requirement at 1.7°C could not be used as a startability requirement. After discussions among DTNSRDC, NAVSSES, ACCUREX, and BFLRF personnel, it was decided that 1.7°C was not necessarily representative of Navy cold starting. A temperature of 5°C was selected as being more representative of actual below decks operation. In addition, 5°C appeared to be a break point on the temperature versus time to start curves for three of the engines. Because of this, 5°C was selected as the test temperature. The consensus was that 5°C would be a test temperature

TABLE 3. Manufacturer's Recommended Engine Break-In Schedules

Time, min	Speed, rpm	Power, kW
	DDA 4-53T	
10	600	0
30	2800	0
10	1500	15
10	2500	65
10	2500	131
Power Check	2800	Maximum
	DDA 4-71TI	
10	600	0
30	1200	0
30	1800	0
30	1200	22
30	1800	45
30	2100	90
30	2300	134
30	2500	168
60	2500	187
60	2500	205
	Westerbeke 4-108	
10	600	0
10	800	0
30	1200	0
30	1800	0
30	1200	2
30	1800	4
30	2100	8
30	2400	13
60	2400	16
60	2400	19
	Cummins NH-220	
10	800	0
To Temperature	1575	82
15	2100	124
15	2100	140
15	2100	148
15	2100	164

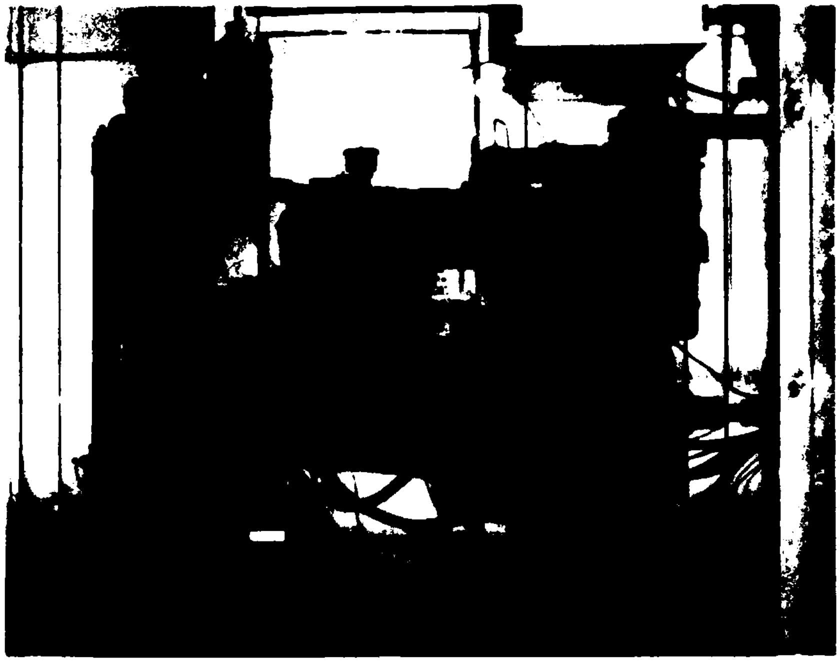

Figure 1. **Cummins NH-220 installed in cold box**

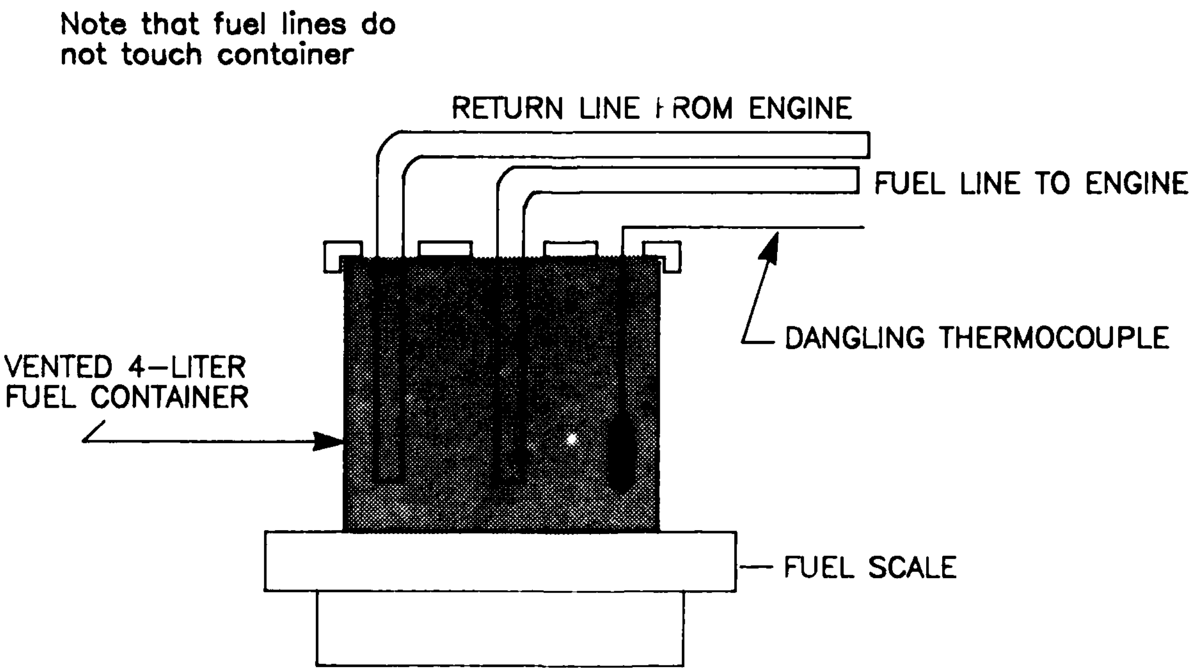

Figure 2. **Fuel supply and return lines**

representative of actual Navy cold starts and still provide good discrimination between test fuels.

Since engine cranking speed is known to be an important variable in engine starting, it was desirable to have the engine cranking systems conform as closely as possible to Navy practice. NAVSSES personnel surveyed shipboard starter arrangements and recommended that air starters be used for cranking. This also allowed for extended cranking periods.

With air starters, the engine cranking speed varies with compressor air pressure. It was decided to hold air pressure to the starting motors constant to maintain the cranking speed. Very large (>600 SCFM) pressure-regulated air supplies and inlet throttling valves were used. Cranking speeds were chosen to correspond to the measured cranking speeds of the engines using standard electric starters. These speeds were 200 rpm for the DDA 4-53T and Cummins NH-220 engines and 225 rpm for the DDA 4-71TI and Westerbeke 4-108 engines. Both air pressure and cranking speed were monitored in order to obtain repeatable cranking conditions. Analysis of data from the Cummins NH-220 engine emphasized that cranking speed was more important than originally estimated. Because of this, an extra air pressure regulator was used on the DDA 4-53T engine.

After the test temperature and cranking speeds were determined, the definitions of a "start" and "no start" were established. A start was defined as a self-sustaining running condition after a finite cranking period. The cranking time was the amount of time that the starter button was held down. In the event that the engine started and died, the starter was energized again and the start time was the cumulative time. A no start was defined as failure to reach a self-sustained running condition after a fixed cranking period. The limit on cranking time was fixed at four times the average starting time at 5°C with the base fuel. Cranking time limits were 37 seconds for the Cummins NH-220, 109 seconds for the DDA 4-71TI, 41 seconds for the Westerbeke 4-108, and 19 seconds for the DDA 4-53T.

During the cold-start testing, some deterioration of the base fuel was noticed as a darkening of the fuel and a rise in ASTM D 2276 particulates. Investigation revealed that the fuel was indeed degrading, but would probably not affect the cold start testing results.(12)

Fuel Blending

Fuels for the cold start tests were blended from the F-76 base fuel and the three low-cetane blending components shown in TABLE 2. All the fuels were free of cetane improver. TABLE 4 shows which fuels were run in each engine. Fuel properties of each of the test fuels are shown in Appendix A. In practice, each fuel was blended volumetrically using a 1000-mL graduated cylinder to measure the blending components. The components were mixed using agitation or mechanical mixing in order to assure homogeneity. Each engine-fuel combination required approximately 12 liters of fuel for testing. Of this amount, 4 liters were used for fuel system flushing, 4 liters were delivered to the analytical laboratory for analysis, and 4 liters were used in the actual start attempt.

TABLE 4. Engine-Fuel Combinations

Fuel Description	DDA 4-53T	DDA 4-71TI	Cummins NH-220	Westerbeke 4-108
Base Fuel (F-76)	X	X	X	X
95%A + 5%G	X	X	X	X
90%A + 10%G	X	X	X	X
87.5A + 12.5G			X	
85%A + 15%G	X	X	X	X
80%A + 20%G	X	X		X
75%A + 25%G		X		X
70%A + 30G				X
65%A + 35%G				X
60%A + 40%G				X
97.5%A + 2.5%Q			X	
95%A + 5%Q	X	X	X	X
92.5%A + 7.5%Q			X	
90%A + 10%Q	X	X	X	X
85%A + 15%Q	X	X		X
80%A + 20%Q	X	X		X
75%A + 25%Q	X	X		X
70%A + 30%Q		X		X
65%A + 35%Q		X		X
97.5%A + 2.5%R			X	
95%A + 5%R	X	X	X	X
92.5%A + 7.5%R			X	
90%A + 10%R	X	X	X	X
87.5A + 12.5R		X		X
85%A + 15%R	X	X	X	X
80%A + 20%R	X			
75%A + 25%R	X			

IV. TEST PROTOCOL

The F-76 base fuel was first introduced into the test engines. Cold starts were performed at temperatures varying from 2°C to ambient in order to examine the startability characteristics of the engines using a fuel typical of shipboard use. In practice, the cold box was sealed, and a 23-hour cold soak used to ensure temperature equilibration. Oil sump temperature was used as the temperature representative of actual test temperature, since the oil sump is a significant thermal mass and is representative of the average engine temperature. The "before" temperatures and fuel weight were recorded, and the cold start performed. During the cranking, the operator visually monitored cranking motor air pressure and cranking speed. Starting of the engine was subjectively determined by the operator, by monitoring the sound, vibration levels, and displayed rpm. After starting, the engine was allowed to idle for a minimum of 10 seconds in order to burn out any liquid fuel remaining in the combustion chambers. The "after" temperatures and fuel weight were then recorded as well as the observed air pressure and cranking speed. This procedure was repeated at target temperatures of 5°, 10°, 16°, and 21°C in order to establish the temperature versus starting time relationship for the base fuel.

The temperature of the cold box was next adjusted to maintain 5°C ± 1°C. The F-76 base fuel was run a number of times to obtain an average starting time for each engine with the base fuel. Next, progressively greater proportions of the low cetane blending components were blended with the base fuel. These blends were run in the cold start procedure until the starting times exceeded four times the average starting time with the base fuel. Each engine-fuel combination was run at least twice, and each blending component (G, Q, or R) was blended in at least four concentrations in each engine. TABLE 4 shows the fuels that were run in each engine. A fuel flush procedure with a fuel filter change was used when a new fuel was introduced into the engine. The fuel flushing procedure is detailed in Appendix B.

V. DISCUSSION OF RESULTS

Figs. 3 through 6 show temperature versus time to start curves for each of the engines using the base fuel. Note that the data plotted in the figures are from a separate set of data and is not the same as shown in Appendix C. The diagrams show that only the

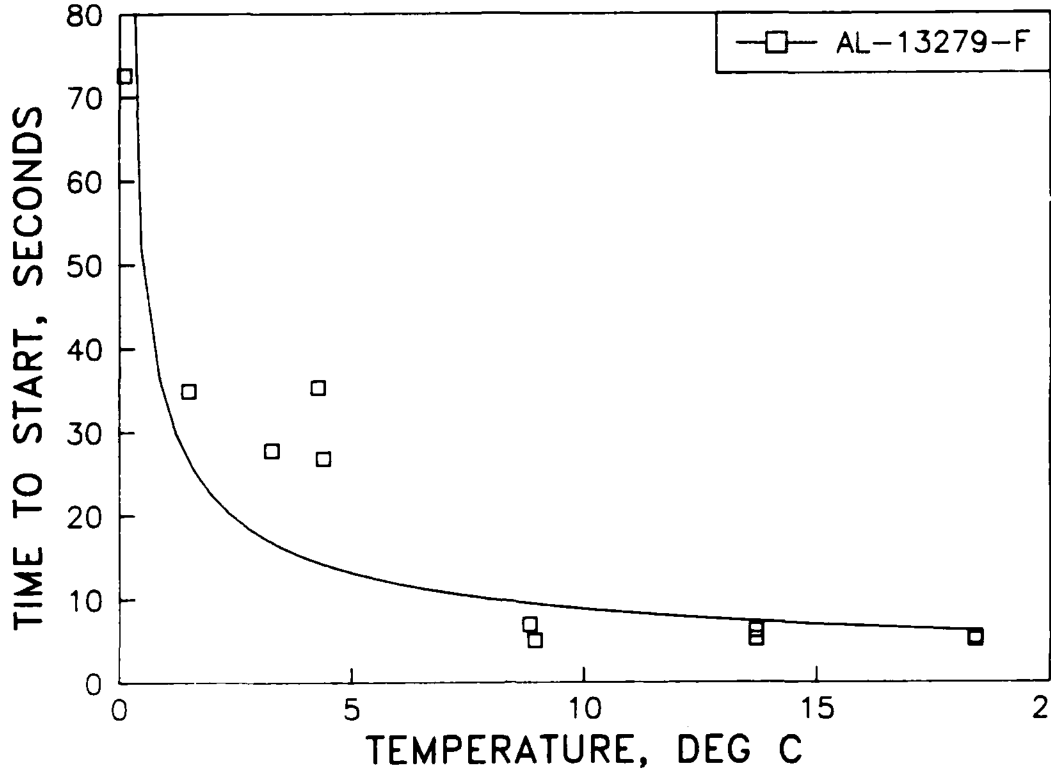

Figure 3. Cummins NH-220 with F-76 at 175 rpm

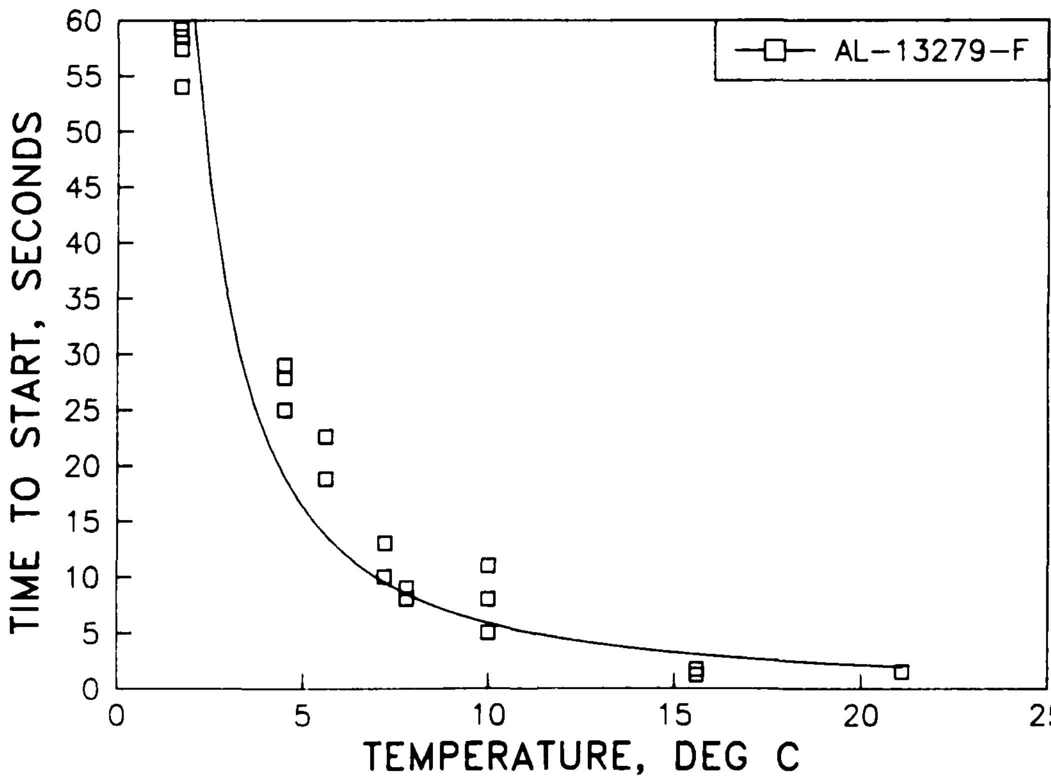

Figure 4. DDA 4-71TI with F-76 at 225 rpm

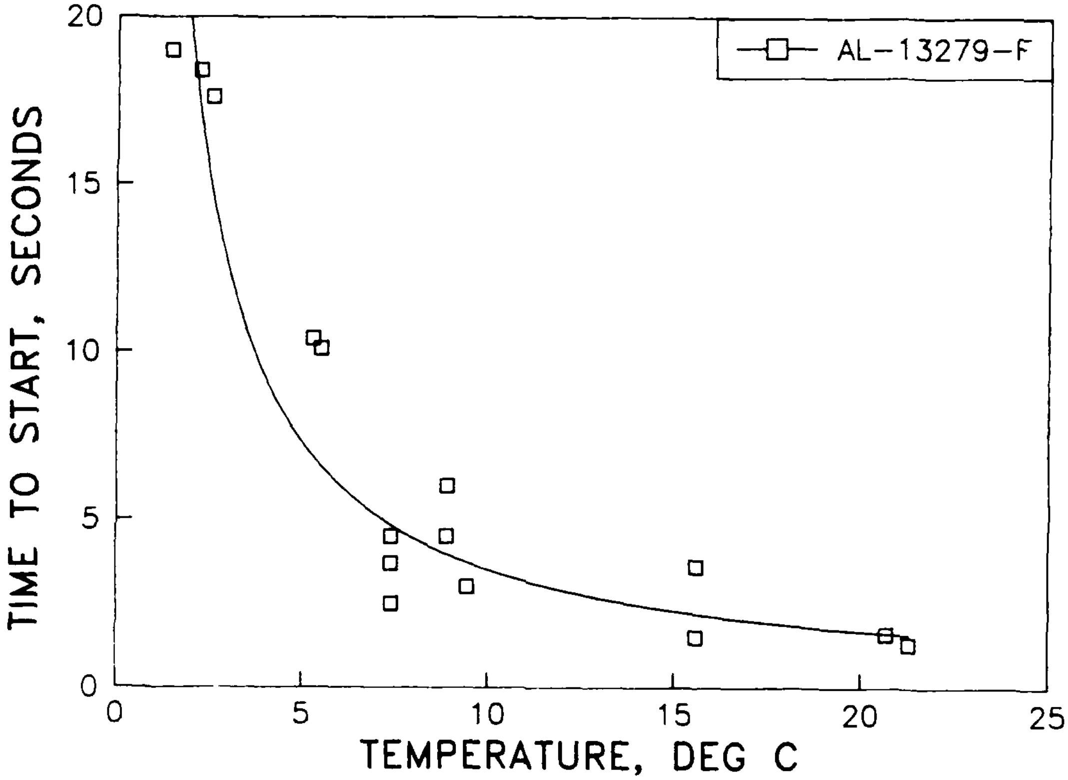

Figure 5. <u>**DDA 4-53T with F-76 at 200 rpm**</u>

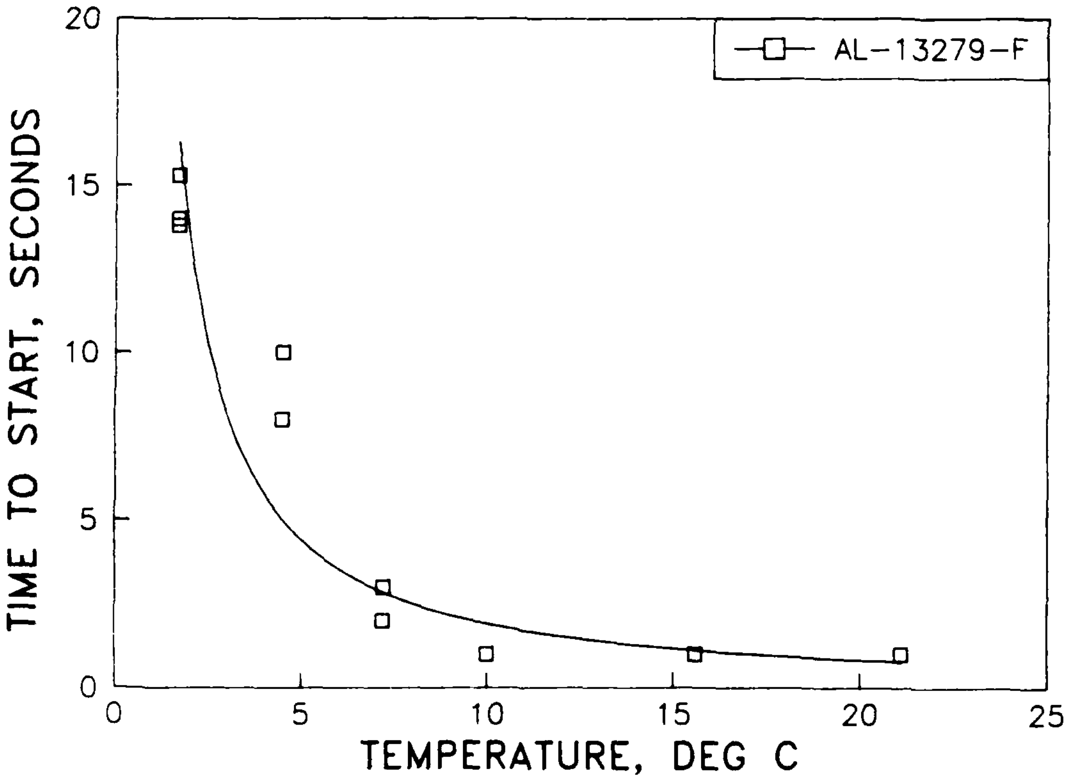

Figure 6. <u>**Westerbeke 4-108 with F-76 at 225 rpm**</u>

Westerbeke 4-108 engine is close to meeting the MIL-E-24455 starting requirement of 10 seconds to start at 1.7°C. The diagrams also show that 5°C is near the break point in the curves, i.e., the point at which small decreases in temperature cause large increases in starting time. The curves in each of the diagrams are intended to indicate trends; they do not represent best fit lines. In order of best to worst startability, the engines rank Westerbeke 4-108, DDA 4-53T, DDA 4-71TI, and Cummins NH-220. This ranking agrees well with the compression ratios of the engines: Westerbeke 4-108 22:1, DDA 4-53T 18.7:1, DDA 4-71TI 17:1, and the Cummins NH-220 15.8:1. Compression ratios play an important role in cold startability, since it determines the adiabatic compression temperature that the air reaches. For a given cranking speed (and fixed injection timing), a higher compression ratio will produce a higher air temperature at the time of fuel injection. As a result of this higher temperature environment, the fuel injected will evaporate and autoignite more readily, resulting in an increased likelihood of the engine starting.

During the starting tests with the Cummins NH-220 engine, a computer-based data acquisition system was used to monitor engine speed. Fig. 7 illustrates typical data

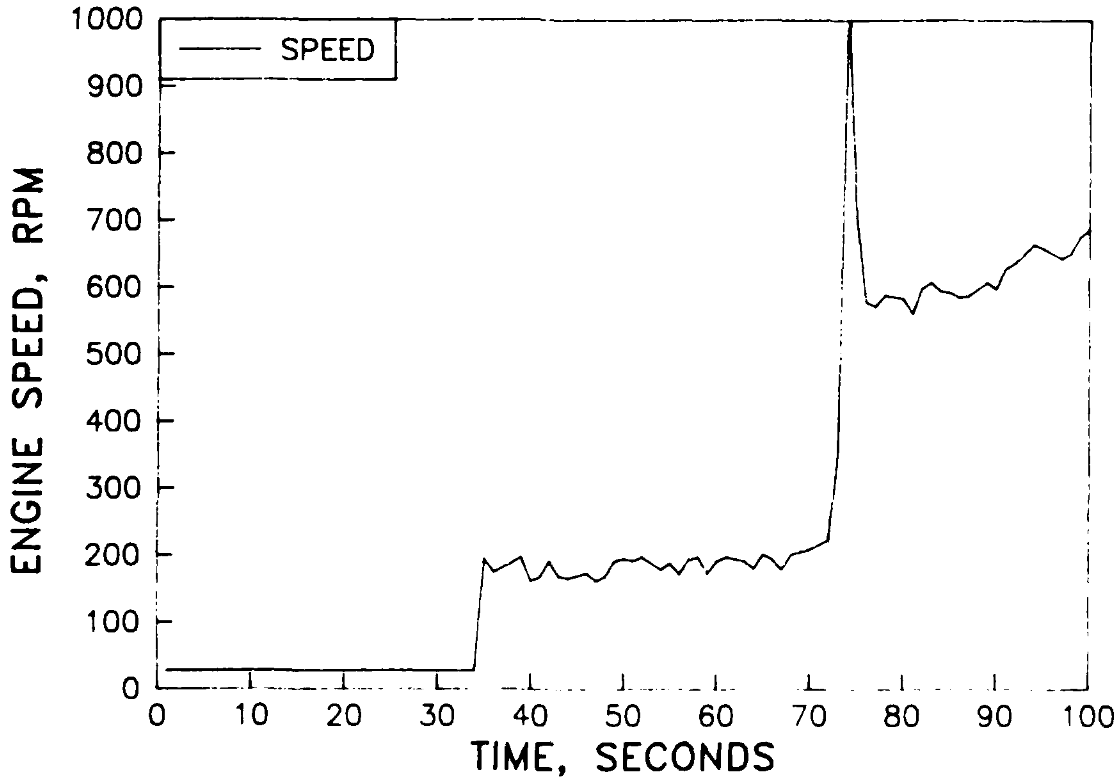

Figure 7. <u>**Engine Speed Versus Time—Cummins NH-220 with AL-13699-F at 200 rpm**</u>

obtained from the data acquisition system. In the figure. speed is represented as a solid line. At approximately 34 seconds on the time scale. the starter is engaged. The engine cranks at 200 rpm for approximately 39 seconds and starts at 73 seconds on the time scale. The engine accelerates to 1000 rpm and then drops to an idle speed of approximately 600 rpm.

Appendix C lists the observation number. date. fuel AL number. cranking speed. and start time for all the starts at 5°C. These are the data on which multiple linear regression analyses were performed. Cranking speeds for the Cummins NH-220 are averages taken from the computer data acquisition system. These speeds are probably the most accurate representation of actual cranking speed. Cranking speeds for the remaining three engines were taken by an operator monitoring a speed display. The operator-read data were subject to "eyeball averaging" (tending to cluster speeds near the desired value) and is. therefore. considered as having more experimental error than the computer-acquired data. In the case of the DDA 4-53T. an extra pressure regulator was used on this engine in order to better control speed.

As noted previously. the cranking speed of the engine is an important factor in the time required to start an engine. While every effort was made to hold cranking speed constant. some variation was evident in the final data. This is especially true with the data from the NH-220 engine. Fortunately in this case. an unbiased method of determining the actual cranking speed was available.

The computer-acquired cranking speeds were measured every second during each starting attempt of the NH-220 engine. These data were reduced by averaging the engine rpm readings that were between 150 and 300. If the engine speed exceeded this band. then fell back into this range. the higher speeds were not included in the average. but the time was counted as cranking time. The time from which the engine first exceeded 150 rpm until the engine speed remained above 500 rpm was the calculated starting time. The cranking rpm's calculated by this method are compared to the cranking speeds as reported by the engine operator in Fig. 8. This gives some indication of the bias introduced by the operator reading a digital speed indicator during cranking. Comparisons of the calculated starting times compared with the operator-reported times agreed closely. and the operator start times were used in analyses.

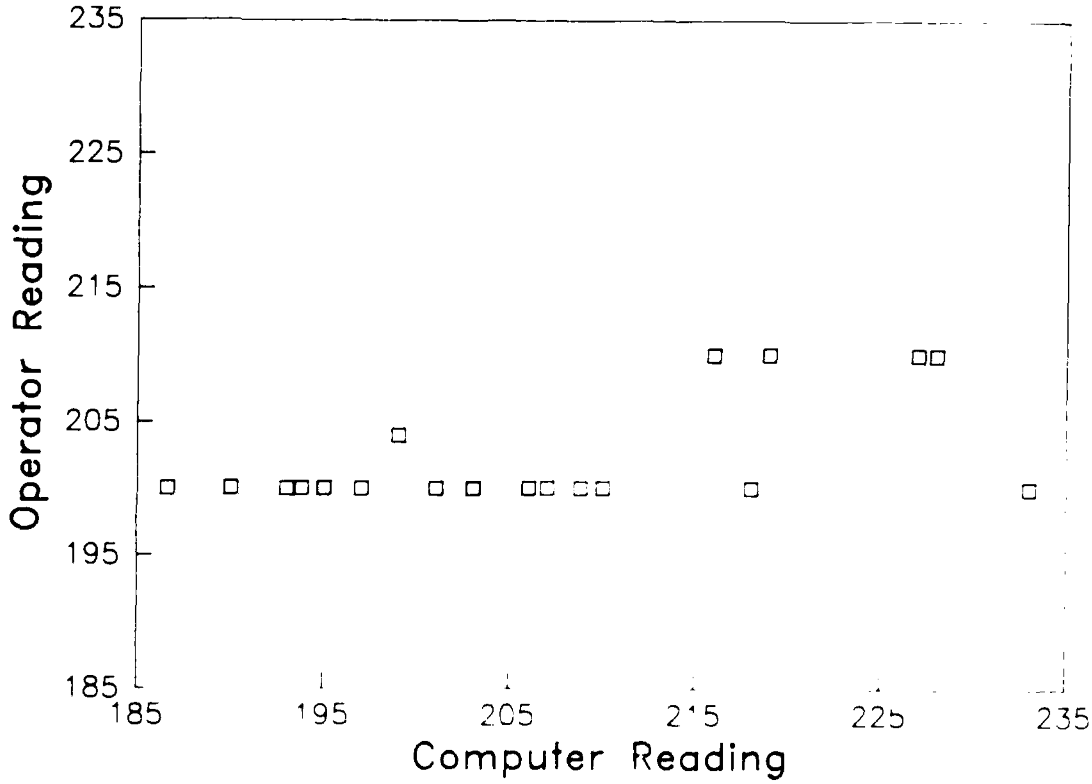

Figure 8. NH-220 Cranking Speed (rpm) Comparison

It is unfortunate that the extent of this cranking speed reporting bias was not recognized until after the DD 4-53T engine test had been completed. However, the test set-up for that engine was considerably better at maintaining a constant cranking speed than during the NH-220 test.

In order to account for the impact of cranking speed on starting times, some model relating the two is needed. As evident from Fig. 9, the relationship is nonlinear. The autoignition process of a fuel requires that a series of physical and chemical processes must be completed before the reactions between the fuel and air in the combustion chamber become exothermic and combustion is self-sustaining. These reaction rates are highly temperature dependent, so that variations in the charge air temperature at the time of fuel injection can have a large impact on the probability of ignition.

The charge air is heated during the compression stroke according to the isentropic temperature volume relationship (Eq. 1).

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \tag{1}$$

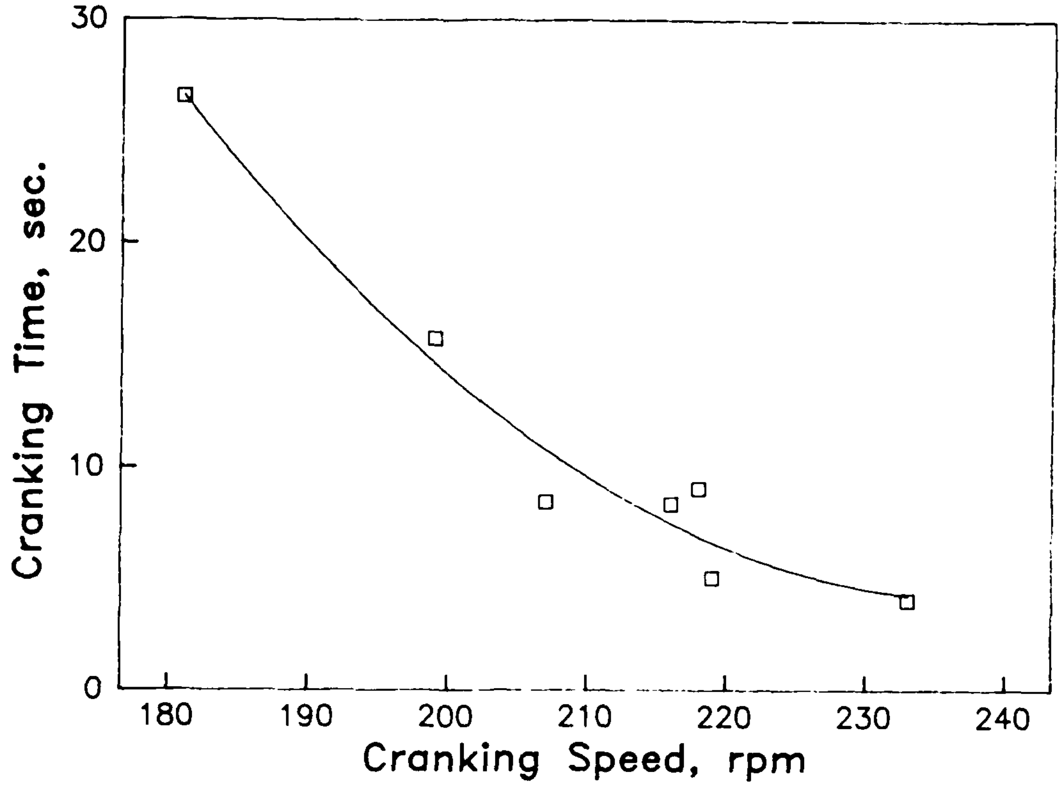

Figure 9. Effect of Cranking Speed on Start Time—Engine: NH-220, Fuel: AL-13279-L

where T_1 and T_2 are the charge temperatures, V_1 and V_2 are the charge volumes, and k is the rate of molal specific heats C_p/C_v.

This process is independent of time. However, as the gas temperature is increased, the gas transfers heat to the cool engine structure. This heat transfer process is time dependent; therefore, the greater the time between the beginning of compression and the beginning of injection, the lower will be the gas temperature at injection.

The preflame (presustained combustion) reactions are temperature dependent and follow an Arrhenius relationship (Eq. 2).

$$K = Ae^{E/RT} \tag{2}$$

where K is the reaction rate constant, A and E are constants for each reaction, R is a constant, and T is the temperature.

This process of heat transfer to the engine structure from the working fluid occurs during each piston stroke. As the process is continued (without the engine starting), the combustion chamber wall temperatures slowly increase. This decreases the ΔT function driving the heat transfer process, reducing the temperature loss during compression. Eventually, the charge air at the time of injection reaches a level so that ignition can occur, and the engine starts.

Figs. 10 through 13 show that the variation in starting time due to cranking speed changes are in the same order of magnitude as the fuel effects on starting time. Thus any variations that were actually due to the cranking speed but were unaccounted for during the analysis would show up as unexplained error.

In accounting for the effects of cranking speed, an equation form that fits the data closely while introducing as few variables into the regression equation as possible should be used. Initial analysis of the physical phenomena indicated that a log-log relationship would best fit the cranking speed versus starting time data. Since the regression analysis

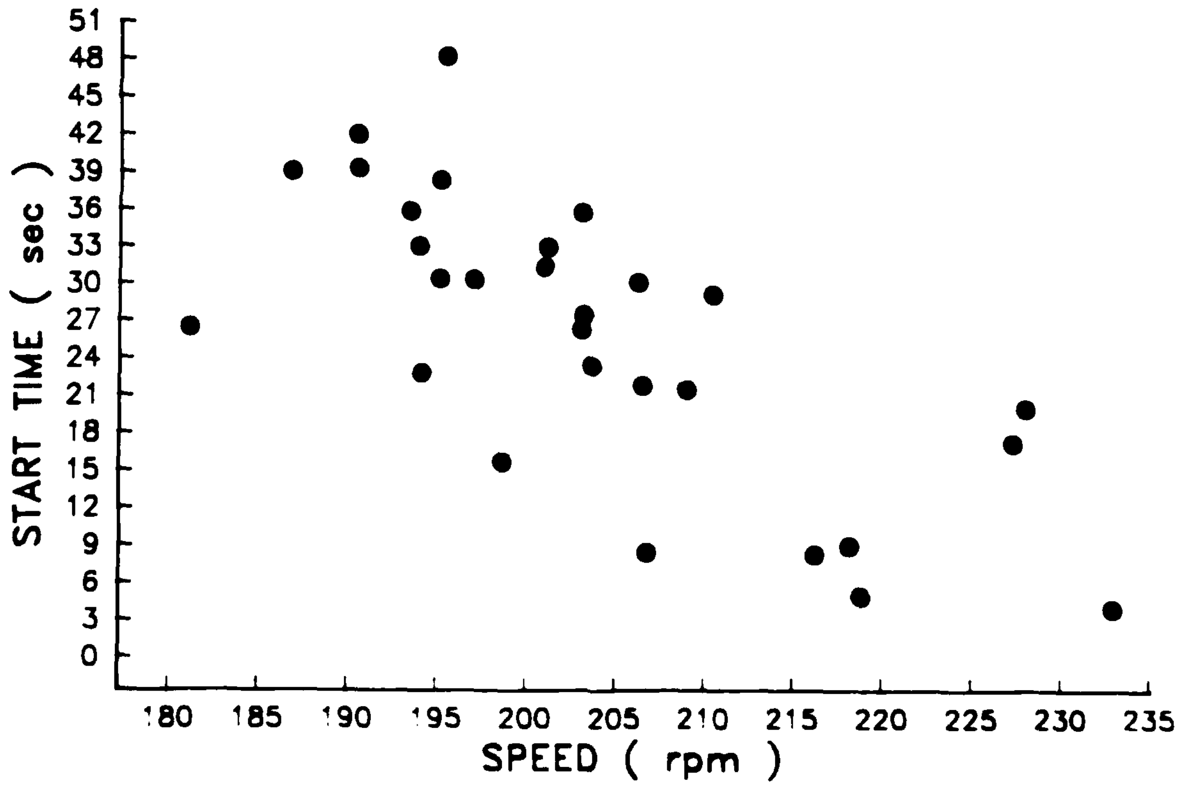

Figure 10. Start Time (sec) Versus Speed (rpm) in the Cummins NH-220 Engine

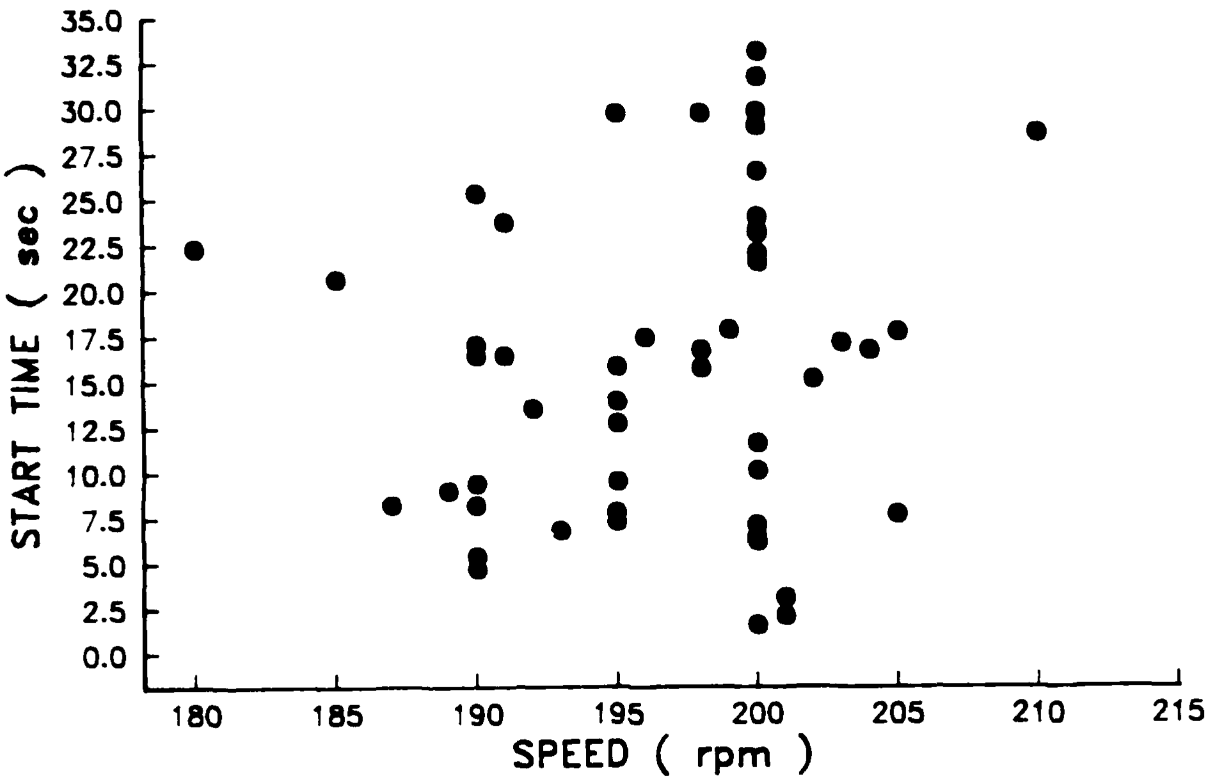

Figure 11. Start Time (sec) Versus Speed (rpm) in the Detroit Diesel Allison 4-53T Engine

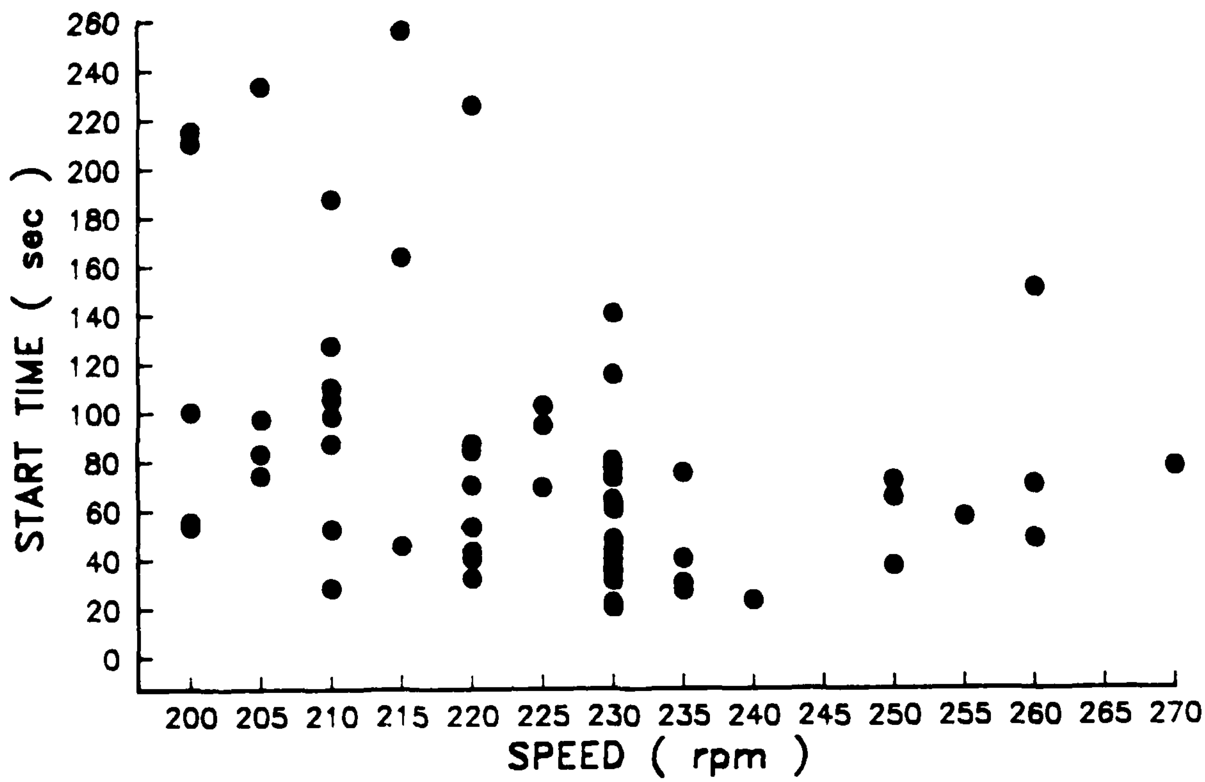

Figure 12. Start Time (sec) Versus Speed (rpm) in the Detroit Diesel Allison 4-71TI Engine

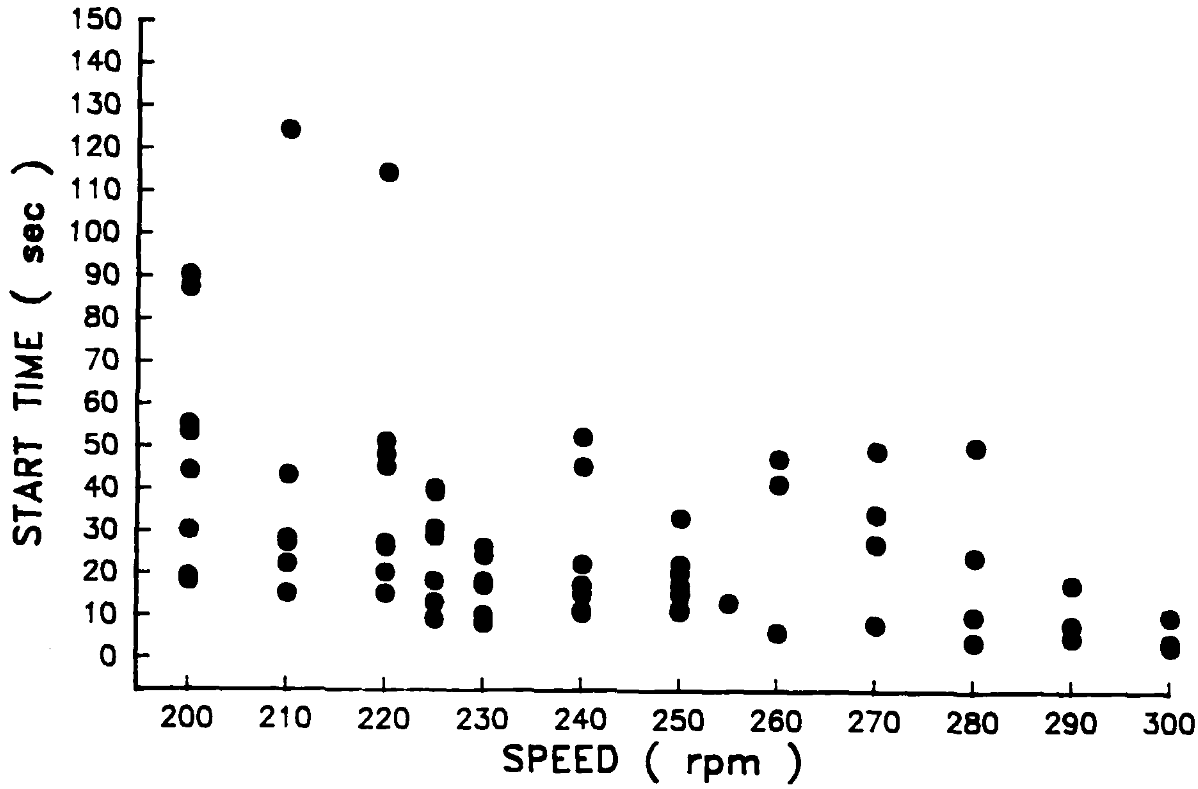

Figure 13. Start Time (sec) Versus Speed (rpm) in the Westerbeke 4-108 Engine

was to be conducted using a stepwise technique, a number of approaches were tried to include a nonlinear relationship for cranking speed without transforming the dependent variable (time to start). This restriction on transformations of the dependent variable was due to the belief that many of the fuel properties were linearly related to starting time.

None of the transformations on starting speed alone provided any better predictive capability than a linear fit. This linear model was inferior to a log-log model fit, but BFLRF statistical capabilities were insufficient to combine this model for the cranking speed-start time relationship with the stepwise analyses of the fuel property effects.

Before beginning the analysis of the fuel effects, the physical properties measured (Appendix A) were evaluated to eliminate any strong linear relationships between the various properties. Pairwise cross-correlations for the four engines are tabulated in

Appendix D. The remaining fuel properties, listed in TABLE 5, were then evaluated for their impact on starting times through the use of a stepwise linear regression procedure.

TABLE 5. Independent Variables Used in the Stepwise Multiple Linear Regression Analysis

Variable	Method
Cranking Speed, rpm	—
Specific Gravity at 15.6°C	D 1298
Flash Point, °C	D 93
Cloud Point, °C	D 2500
Pour Point, °C	D 97
K Viscosity at 40°C, cSt	D 445
30% Boiling Point, °C	D 2887
70% Boiling Point, °C	D 2887
Aniline Point, °C	D 611
Mono-, di-, and tri-aromatics, vol%	NMR
Autoignition Temp, °C	E 659
Cetane Number	D 613
Freezing Point, °C	D 2386

A number of transformations were also examined. The initial premise underlying this analysis was that certain physical and chemical properties of the fuel affect the engine startability. The fuel viscosity and surface tension may affect the amount of spray atomization, and the boiling point distribution of the fuel may change the rate of fuel vapor formation and fuel-air mixing rates. The chemical structure of the fuel molecules affect the speed of the preflame reactions. Historically, all these complex and interrelated effects have been expressed by the cetane number. Since all diesel engines are not designed identically to the CFR cetane engine, each engine may respond to fuel property variations in a manner not completely predicted by cetane number.

To examine this, the fuel property analysis was first conducted with cetane number excluded from consideration. After an acceptable model was developed, the analysis was repeated, forcing the inclusion of cetane number. This would provide some idea of the fuel properties that were encompassed in the cetane number. The results of these analyses are given in TABLES 6 through 9.

TABLE 6. Multiple Linear Regression Statistics for the Cummins NH-220 Engine

Cetane Number Excluded

Number of Data Points:	29
Multiple R^2:	0.8805
Standard Error of Estimate:	4.2298
Dependent Variable:	Start Time

Variable	Coefficient	Standard Error	T	P*
Intercept	298.61	21.89	13.64	0.0001
Speed	-0.3759	0.0728	-5.16	0.0001
Pour Point	2.749	0.5850	4.70	0.0001
Aniline Pt	-2.432	0.2830	-8.60	0.0001

Cetane Number Forced In

Cetane number and the intercept term are collinear. Therefore, the effects of cetane number on other fuel properties cannot be analyzed.

* The P value represents the probability that a T statistic would obtain a greater absolute value than that observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient, and it is calculated by dividing the estimated coefficient by its estimated standard error. A P value of 0.05 represents a 5-percent level of significance.

TABLE 7. Multiple Linear Regression Statistics for the DDA 4-53T Engine

Cetane Number Excluded

Number of Data Points:	52
Multiple R^2:	0.6160
Standard Error of Estimate:	5.5289
Dependent Variable:	Start Time

Variable	Coefficient	Standard Error	T	P*
Intercept	84.878	8.475	10.02	0.0001
K. Vis at 40,C	17.006	4.249	4.003	0.0002
Aniline Pt	-1.933	0.2429	-7.96	0.0001

Cetane Number Forced In

Cetane number is not a significant predictor variable (P value = .51). Viscosity and aniline point remained in the regression equation as significant predictor variables.

* The P value represents the probability that a T statistic would obtain a greater absolute value than that observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient, and it is calculated by dividing the estimated coefficient by its estimated standard error. A P value of 0.05 represents a 5-percent level of significance.

TABLE 8. Multiple Linear Regression Statistics for the DDA 4-71TI Engine

Cetane Number Excluded

Number of Data Points: 60
Multiple R^2: 0.7588
Standard Error of Estimate: 0.31403

Dependent Variable: Log (Start Time)

Variable	Coefficient	Standard Error	T	P*
Intercept	11.742	0.8345	14.07	0.0001
Aniline Pt	-0.1041	0.0097	-10.72	0.0001
Speed	-0.008299	0.00248	-3.35	0.0015
Di-aromatics	0.04847	0.01940	2.499	0.0154

Cetane Number Forced In

Number of Date Points: 60
Multiple R^2: 0.7941
Standard Error of Estimate: 0.28758

Dependent Variable: Log (Start Time)

Variable	Coefficient	Standard Error	T	P*
Intercept	15.109	0.7783	19.41	0.0001
Cetane	-0.2155	0.01558	-13.84	0.0001
Speed	-0.006118	0.00228	-2.69	0.0094

* The P value represents the probability that a T statistic would obtain a greater absolute value than that observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient, and it is calculated by dividing the estimated coefficient by its estimated standard error. A P value of 0.05 represents a 5-percent level of significance.

TABLE 9. Multiple Linear Regression Statistics for the Westerbeke 4-108 Engine

Cetane Number Excluded

Number of Data Points: 70
Multiple R^2: 0.7391
Standard Error of Estimate: 0.43217

Dependent Variable: Log (Start Time)

Variable	Coefficient	Standard Error	T	P*
Intercept	15.281	1.5025	10.17	0.0001
Speed	-0.014634	0.00192	-7.63	0.0001
Cloud Pt	0.10089	0.04954	2.037	0.0458
Flash Pt	-0.0239	0.01336	-1.787	0.0787
Aniline Pt	-0.0759	0.01097	-6.916	0.0001
Freeze Pt	0.13076	0.03952	3.309	0.0015

Cetane Number Included

Number of Date Points: 70
Multiple R^2: 0.7327
Standard Error of Estimate: 0.43744

Dependent Variable: Log (Start Time)

Variable	Coefficient	Standard Error	T	P*
Intercept	16.9940	1.64592	10.325	0.0001
Cetane	-0.1467	0.02183	-6.720	0.0001
Speed	-0.01266	0.001963	-6.451	0.0001
Cloud Pt	0.08338	0.48866	1.706	0.0928
Flash Pt	-0.03054	0.013212	-2.312	0.0240
Freeze Pt	0.11554	0.040548	2.850	0.0059

* The P value represents the probability that a T statistic would obtain a greater absolute value than that observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient, and it is calculated by dividing the estimated coefficient by its estimated standard error. A P value of 0.05 represents a 5-percent level of significance.

Of interest is the inclusion of the cloud, pour, and freeze points as fuel properties important to low-temperature startability. Of course, if the fuel temperature is below the cloud point, then filter plugging and flow problems would interfere with engine

operations. However. in this program all the fuel blends had cloud points well below the test temperature so that these flow problems would not appear. It is believed that these two fuel properties were important indicators which provided information on the number and lengths of the paraffinic molecules in the fuel.

Through the literature. the ring-type structures in the fuel have been used as ignition quality indicators. These have generally been measured either through the aromatic content. which fails to account for naphthenic rings. or by the aniline point. The analysis presented here seems to indicate that the straight-chain structure. such as chain lengths and degree of branching. may be both important and poorly measured with conventional fuel analysis procedures. The research being done by the National Research Council of Canada (14) and by Southwest Research Institute (13) on using proton nuclear magnetic resonance measurements of fuel structure for predicting cetane number have supported this.

The more conventionally measured overt physical properties of fuels do not provide a good indication of the structure of the paraffinic fraction. independent of other related properties (i.e.. viscosity. boiling point distribution. etc.). The inclusion of cloud. pour. and freeze points as significant startability predictors indicates that these properties may be useful indicators of paraffinic structure.

VI. CONCLUSIONS

- The current Navy high-speed diesel engines evaluated in this project do not meet the MIL-E-24455 cold-start requirement of 10 seconds at 1.7°C.

- As anticipated. increased engine compression ratio aids cold startability.

- Cranking speed is much more important in determining startability than was first thought. Cranking speed is also very difficult to control closely. Future work should accurately and frequently record speed during cranking so that average cranking speed can be accurately determined.

- The ability to crank for extended periods of time greatly aids cold startability. Air starters are well suited to extended cranking times.

- The fuel properties identified in this program provide an improved estimate of Navy engine low-temperature startability.

VII. RECOMMENDATIONS

- Future cold start work in diesel engines should utilize large (>600 SCFM) air compressors and air starters to crank the engine. Inlet air throttling and oil mist lubrication should be used on the air starters.

- Cranking speed should be continuously recorded throughout the start attempt. This recording will allow small but important speed variations to be accounted for in the final analysis. An alternate arrangement may record the total numer of engine revolutions and the duration of the cranking event.

- Engines exposed to temperatures of 5°C or less will benefit from higher compression ratios. In extremely cold temperatures. existing engines will require air starters to start successfully.

- The use of cloud point or freeze point measurements to improve engine startability estimates should be investigated further. This addition to conventional cetane number estimation may allow improved field screening of fuels for Navy use.

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LIST OF ABBREVIATIONS

AR - Naval Ship Designation

ASTM - American Society for Testing and Materials

AVM - Naval Ship Designation

BFLRF - Belvoir Fuels and Lubricants Research Facility (SwRI)

cSt - Centistokes

C_p - Molal Specific Heat at Constant Pressure

C_v - Molal Specific Heat at Constant Volume

CFR - Coordinating Fuels Research

DTNSRDC - David Taylor Naval Ship Research and Development Center

DDA - Detroit Diesel Allison

°C - Degrees Centigrade

°F - Degrees Fahrenheit

DFM - Diesel Fuel, Marine (MIL-F-16884G Fuel Oil)

k - Reaction Rate Constant

K - Ratio of Molal Specific Heats

kW - Kilowatts

MFRD - Mobility Fuels Research and Development

min - Minutes

mL - Milliliters

NA - Not Available

NATO - North Atlantic Treaty Organization

NAVSSES - Naval Ship Systems Engineering Station

ND - Navy Distillate (MIL-F-24397)

NMR - Nuclear Magnetic Resonance

NSFO - Navy Special Fuel Oil (MIL-F-859E)

R^2 - Coefficient of Determination

rpm - Revolutions Per Minute

SCFM - Standard Cubic Feet Per Minute

SwRI - Southwest Research Institute

TEMP - Temperature

T_1, T_2 - Temperatures

V_1, V_2 - Volumes

VOL - Volume

APPENDIX A
TEST FUEL PROPERTIES

PROPERTY	METHOD	13279	13634	13639	13664	13684	13692	13694
FUEL BLEND	BFLRF	100A	95A/5G	90A/10G	85A/15G	87.5A/12.5G	95A/5Q	90A/10Q
SPEC. GRAVITY @ 15.6 C	D1298	0.8484	0.8519	0.8545	0.8565	0.855	0.854	0.8597
API GRAVITY, DEG.	D1298	35.2	34.6	34.1	33.7	34	34.2	33.1
FLASH POINT, C	D9356	77	75	74	73	73	76	76
CLOUD POINT, C	D2500	-13	-13	-14	-16	-15	-14	-12
POUR POINT, C	D97	-17	-13	-17	-19	-17	-14	-14
K VIS @ 40 C, cSt	D445	2.75	2.67	2.53	2.44	2.5	2.77	2.75
K VIS @ 5 C, cSt	D445	6.65	6.28	5.91	5.6	5.76	6.61	6.64
AROMATICS, VOL %	D1319	26.3	28.9	33.5	35.4	33	28.4	29.7
AUTOIGNITION TEMP., C	E659	189	186	185	189	190	185	188
ANILINE PT, C	D611	66.1	62.7	62.8	55.6	57.6	63	60.5
CETANE NUMBER	D613	48.7	46.2	45.2	43.6	44.3	47	44.9
D2887 IBP, C	D2887	133	136	136	138	135	136	137
D2887 10% PT, C	D2887	209	208	205	203	203	210	211
D2887 20% PT, C	D2887	230	227	223	220	221	231	233
D2887 30% PT, C	D2887	246	241	238	236	236	247	248
D2887 40% PT, C	D2887	259	256	254	251	252	259	260
D2887 50% PT, C	D2887	273	270	266	262	264	273	274
D2887 60% PT, C	D2887	287	284	281	277	278	288	288
D2887 70% PT, C	D2887	304	302	298	294	296	304	305
D2887 80% PT, C	D2887	322	320	317	314	315	321	322
D2887 90% PT, C	D2887	346	345	343	340	342	346	346
D2887 99.5% PT, C	D2887	401	405	405	402	402	402	403
D86 IBP, C	D86	192	198	195	182	194	199	199
D86 10% PT, C	D86	222	224	221	213	219	227	227
D86 20% PT, C	D86	236	235	231	226	228	237	237
D86 30% PT, C	D86	244	243	240	234	238	246	246
D86 40% PT, C	D86	253	251	249	244	248	256	256
D86 50% PT, C	D86	262	263	260	254	258	266	266
D86 60% PT, C	D86	273	274	271	265	269	277	277
D86 70% PT, C	D86	287	287	285	278	282	288	288
D86 80% PT, C	D86	303	303	301	293	298	304	304
D86 90% PT, C	D86	322	325	323	317	319	324	324
D86 95% PT, C	D86	339	344	343	335	336	338	339
D86 EP, C	D86	348	353	352	346	349	353	352
D86 % RECOVERED	D86	98.5	99	99	99	99	99	99
D86 RESIDUE, %	D86	1.5	1	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	3	4	5	5	5	5	5
% MONO-AROMATIC RING H	NMR	2	2	2	3	2	1	1
% ALPHA H	NMR	6	7	8	8	9	7	7
% H ON CARBON	NMR	51	50	48	48	50	50	49
% H ON TERMINAL CARBON	NMR	36	35	34	33	32	35	35

* Rounding off of these NMR values may result in totals other than 100%.

PROPERTY	METHOD	13699	13700	13706	13736	13737	13803	13850
FUEL BLEND	DFLRF	92.5A/7.50	97.5A/2.50	95A/5R	90A/10R	92.5A/7.5R	97.5A/2.5R	85A/15R
SPEC. GRAVITY @ 15.6 C	D1298	0.8565	0.8514	0.8499	0.8519	0.8504	0.8493	0.8524
API GRAVITY, DEG.	D1298	33.7	34.7	35	34.6	34.9	35.8	34.5
FLASH POINT, C	D9356	76	76	68	64	66	71	59
CLOUD POINT, C	D2500	-13	-12	-12	-15	-12	-13	-14
POUR POINT, C	D97	-17	-14	-16	-15	-15	-16	-21
K VIS @ 40 C, cSt	D445	2.75	2.74	2.53	2.28	2.39	2.62	2.09
K VIS @ 5 C, cSt	D445	6.64	6.59	5.83	5.05	5.44	6.25	4.44
AROMATICS, VOL %	D1319	31.2	26.4	30.1	32.0	31.2	29.1	30
AUTOIGNITION TEMP., C	E659	188	191	188	189	186	188	186
ANILINE PT, C	D611	61.7	64.5	61.9	58	60.9	64.6	53.6
CETANE NUMBER	D613	45.6	48.1	46.3	43.0	47	48.4	41.8
D2887 IBP, C	D2887	137	134	136	139	137	136	139
D2887 10% PT, C	D2887	211	209	197	171	181	204	167
D2887 20% PT, C	D2887	232	230	220	210	216	226	194
D2887 30% PT, C	D2887	247	245	238	232	235	241	221
D2887 40% PT, C	D2887	259	259	255	250	254	257	241
D2887 50% PT, C	D2887	274	272	270	264	267	272	258
D2887 60% PT, C	D2887	288	287	284	280	282	286	275
D2887 70% PT, C	D2887	305	304	302	297	300	303	293
D2887 80% PT, C	D2887	321	321	319	317	319	320	314
D2887 90% PT, C	D2887	346	345	345	343	344	346	340
D2887 99.5% PT, C	D2887	403	403	402	401	402	402	401
D86 IBP, C	D86	190	181	163	167	173	185	150
D86 10% PT, C	D86	227	218	205	196	203	214	189
D86 20% PT, C	D86	237	229	222	216	219	231	202
D86 30% PT, C	D86	244	241	235	232	233	241	220
D86 40% PT, C	D86	256	249	247	245	247	252	230
D86 50% PT, C	D86	267	261	257	257	258	263	252
D86 60% PT, C	D86	277	272	268	268	269	273	265
D86 70% PT, C	D86	289	284	281	282	282	287	279
D86 80% PT, C	D86	305	301	297	298	298	301	296
D86 90% PT, C	D86	324	322	317	318	318	321	317
D86 95% PT, C	D86	339	336	331	335	333	329	331
D86 EP, C	D86	351	347	346	348	349	349	348
D86 % RECOVERED	D86	99	99	99	99	99	99	99
D86 RESIDUE, %	D86	1	1	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	4	4	4	5	5	4	4
% MONO-AROMATIC RING H	NMR	2	2	2	3	2	1	4
% ALPHA H	NMR	7	6	7	10	8	7	11
% H ON CARBON	NMR	50	51	50	48	48	51	45
% H ON TERMINAL CARBON	NMR	33	35	35	33	34	33	33

* Rounding off of these NMR values may result in totals other than 100%.

PROPERTY	METHOD	13864	13865	13866	13867	13868	13869	13870
FUEL BLEND	BFLRF	95A/5G	90A/10G	85A/15G	80A/20G	70A/30G	75A/25G	60A/40G
SPEC. GRAVITY @ 15.6 C	D1298	0.8519	0.8545	0.8565	0.8586	0.8633	0.8612	0.8681
API GRAVITY, DEG.	D1298	34.6	34.1	33.7	33.2	32.4	32.8	31.5
FLASH POINT, C	D9356	75	74	73	72	72	73	62
CLOUD POINT, C	D2500	-13	-14	-16	-16	-14	-14	-16
POUR POINT, C	D97	-13	-17	-19	-21	-21	-21	-24
K VIS @ 40 C, cSt	D445	2.67	2.53	2.44	2.36	2.23	2.3	2.06
K VIS @ 5 C, cSt	D445	6.28	5.91	5.6	5.4	4.98	5.19	4.51
AROMATICS, VOL %	D1319	28.9	33.5	35.4	43.4	43.4	41.9	50
AUTOIGNITION TEMP., C	E659	186	185	189	187	188	187	190
ANILINE PT, C	D611	62.7	62.8	55.6	53.6	47.3	50.4	39
CETANE NUMBER	D613	46.2	45.2	43.6	40.7	40.7	40.7	36.7
D2887 IBP, C	D2887	136	136	138	139	140	140	136
D2887 10% PT, C	D2887	208	205	203	200	197	198	194
D2887 20% PT, C	D2887	227	223	220	217	213	215	209
D2887 30% PT, C	D2887	241	238	236	234	228	230	222
D2887 40% PT, C	D2887	256	254	251	246	238	242	235
D2887 50% PT, C	D2887	270	266	262	259	254	257	248
D2887 60% PT, C	D2887	284	281	277	274	267	271	260
D2887 70% PT, C	D2887	302	298	294	290	283	287	275
D2887 80% PT, C	D2887	320	317	314	311	304	308	297
D2887 90% PT, C	D2887	345	343	340	339	333	336	328
D2887 99.5% PT, C	D2887	405	405	402	399	401	402	398
D86 IBP, C	D86	190	195	182	190	185	191	184
D86 10% PT, C	D86	224	221	213	213	216	213	209
D86 20% PT, C	D86	235	231	226	225	221	223	217
D86 30% PT, C	D86	243	240	234	234	229	232	225
D86 40% PT, C	D86	251	249	244	243	237	241	233
D86 50% PT, C	D86	263	260	254	253	247	251	241
D86 60% PT, C	D86	274	271	265	263	257	262	251
D86 70% PT, C	D86	287	285	278	277	271	275	264
D86 80% PT, C	D86	303	301	293	293	289	292	281
D86 90% PT, C	D86	325	323	317	316	314	316	309
D86 95% PT, C	D86	344	343	335	331	335	335	331
D86 EP, C	D86	353	352	346	348	344	345	342
D86 % RECOVERED	D86	99	99	99	99	99	98	98
D86 RESIDUE, %	D86	1	1	1	1	1	2	2
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	4	5	5	NA	5	5	6
% MONO-AROMATIC RING H	NMR	2	2	3	NA	4	3	5
% ALPHA H	NMR	7	8	8	NA	13	12	16
% H ON CARBON	NMR	50	48	48	NA	46	46	43
% H ON TERMINAL CARBON	NMR	35	34	33	NA	29	31	28

* Rounding off of these NMR values may result in totals other than 100%.

PROPERTY	METHOD	13871	13894	13907	13908	13909	13990	13991
FUEL BLEND	BFLRF	65A/35G	95A/5G	90A/10G	85A/15G	80A/20G	95A/5G	90A/10G
SPEC. GRAVITY @ 15.6 C	D1298	0.8654	0.8519	0.8545	0.8565	0.8586	0.854	0.8597
API GRAVITY, DEG.	D1298	32	34.6	34.1	33.7	33.2	34.2	33.1
FLASH POINT, C	D9356	69	75	74	73	72	76	76
CLOUD POINT, C	D2500	-17	-13	-14	-16	-16	-14	-12
POUR POINT, C	D97	-24	-13	-17	-19	-21	-14	-14
K VIS @ 40 C, cSt	D445	2.14	2.67	2.53	2.44	2.36	2.77	2.75
K VIS @ 5 C, cSt	D445	4.7	6.28	5.91	5.6	5.4	6.61	6.64
AROMATICS, VOL %	D1319	46.9	28.9	33.5	35.4	43.4	28.4	29.7
AUTOIGNITION TEMP., C	E659	187	186	185	189	187	185	188
ANILINE PT, C	D611	43	62.7	62.8	55.6	53.6	63	60.5
CETANE NUMBER	D613	37.5	46.2	45.2	43.6	40.7	47	44.9
D2887 IBP, C	D2887	138	136	136	138	139	136	137
D2887 10% PT, C	D2887	196	208	205	203	200	210	211
D2887 20% PT, C	D2887	211	227	223	220	217	231	233
D2887 30% PT, C	D2887	225	241	238	236	234	247	248
D2887 40% PT, C	D2887	237	256	254	251	246	259	260
D2887 50% PT, C	D2887	251	270	266	262	259	273	274
D2887 60% PT, C	D2887	263	284	281	277	274	288	288
D2887 70% PT, C	D2887	280	302	298	294	290	304	305
D2887 80% PT, C	D2887	302	320	317	314	311	321	322
D2887 90% PT, C	D2887	331	345	343	340	339	346	346
D2887 99.5% PT, C	D2887	399	405	405	402	399	402	403
D86 IBP, C	D86	185	198	195	182	190	199	199
D86 10% PT, C	D86	209	224	221	213	213	227	227
D86 20% PT, C	D86	218	235	231	226	225	237	237
D86 30% PT, C	D86	227	243	240	234	234	246	246
D86 40% PT, C	D86	236	251	249	244	243	256	256
D86 50% PT, C	D86	245	263	260	254	253	266	266
D86 60% PT, C	D86	257	274	271	265	263	277	277
D86 70% PT, C	D86	269	287	285	278	277	288	288
D86 80% PT, C	D86	285	303	301	293	293	304	304
D86 90% PT, C	D86	314	325	323	317	316	324	324
D86 95% PT, C	D86	333	344	343	335	331	338	339
D86 EP, C	D86	342	353	352	346	348	353	352
D86 % RECOVERED	D86	98	99	99	99	99	99	99
D86 RESIDUE, %	D86	2	1	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	5	4	5	5	NA	5	5
% MONO-AROMATIC RING H	NMR	4	2	2	3	NA	1	1
% ALPHA H	NMR	14	7	8	8	NA	7	7
% H ON CARBON	NMR	44	50	48	48	NA	50	49
% H ON TERMINAL CARBON	NMR	30	35	34	33	NA	35	35

* Rounding off of these NMR values may result in totals other than 100%.

PROPERTY	METHOD	13992	13993	14003	14004	14005	14006	14019
FUEL BLEND	BFLRF	85A/15Q	80A/20Q	95A/5R	90A/10R	85A/15R	80A/20R	95A/5Q
SPEC. GRAVITY @ 15.6 C	D1298	0.8644	0.8708	0.8499	0.8519	0.8524	0.8534	0.854
API GRAVITY, DEG.	D1298	32.2	31	35	34.6	34.5	34.3	34.2
FLASH POINT, C	D9356	77	77	68	64	59	58	76
CLOUD POINT, C	D2500	-13	-12	-12	-15	-14	-18	-14
POUR POINT, C	D97	-16	-15	-16	-15	-21	-21	-14
K VIS @ 40 C, cSt	D445	2.76	2.75	2.53	2.28	2.09	1.94	2.77
K VIS @ 5 C, cSt	D445	6.7	6.73	5.83	5.05	4.44	3.98	6.61
AROMATICS, VOL %	D1319	42.3	45.7	30.1	32.8	38	43.3	28.4
AUTOIGNITION TEMP., C	E659	186	187	188	189	186	186	185
ANILINE PT, C	D611	58.6	55.5	61.9	58	53.6	50.2	63
CETANE NUMBER	D613	43.5	41.8	46.3	43.8	41.8	40.1	47
D2887 IBP, C	D2887	138	139	136	139	139	138	136
D2887 10% PT, C	D2887	212	213	197	171	167	164	210
D2887 20% PT, C	D2887	233	233	220	210	194	173	231
D2887 30% PT, C	D2887	249	250	238	232	221	211	247
D2887 40% PT, C	D2887	260	261	255	250	241	235	259
D2887 50% PT, C	D2887	274	275	270	264	258	254	273
D2887 60% PT, C	D2887	288	289	284	280	275	272	288
D2887 70% PT, C	D2887	304	304	302	297	293	288	304
D2887 80% PT, C	D2887	323	323	319	317	314	311	321
D2887 90% PT, C	D2887	347	347	345	343	340	338	346
D2887 99.5% PT, C	D2887	403	404	402	401	401	399	402
D86 IBP, C	D86	178	181	163	167	158	163	199
D86 10% PT, C	D86	224	226	205	196	189	179	227
D86 20% PT, C	D86	237	237	222	216	202	197	237
D86 30% PT, C	D86	247	246	235	232	220	212	246
D86 40% PT, C	D86	256	256	247	245	238	233	256
D86 50% PT, C	D86	265	265	257	257	252	250	266
D86 60% PT, C	D86	276	275	268	268	265	264	277
D86 70% PT, C	D86	288	287	281	282	279	278	288
D86 80% PT, C	D86	302	301	297	298	296	296	304
D86 90% PT, C	D86	321	320	317	318	317	319	324
D86 95% PT, C	D86	335	334	331	335	331	338	338
D86 EP, C	D86	349	349	346	348	348	347	353
D86 % RECOVERED	D86	99	99	99	99	99	99	99
D86 RESIDUE, %	D86	1	1	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	6	7	4	5	4	5	5
% MONO-AROMATIC RING H	NMR	1	2	2	3	4	4	1
% ALPHA H	NMR	8	9	7	10	11	14	7
% H ON CARBON	NMR	50	46	50	48	45	45	50
% H ON TERMINAL CARBON	NMR	32	34	35	33	33	29	35

* Rounding off of these NMR values may result in totals other than 100%.

PROPERTY	METHOD	14020	14021	14022	14023	14024	14025	14030
FUEL BLEND	AFLRF	90A/10Q	85A/15Q	80A/20Q	75A/25Q	70A/30Q	65A/35Q	95A/5R
SPEC. GRAVITY @ 15.6 C	D1298	0.8597	0.8644	0.8708	0.8745	0.88	0.8849	0.8499
API GRAVITY, DEG.	D1298	33.1	32.2	31	30.3	29.3	28.4	35
FLASH POINT, C	D93S6	76	77	77	77	78	76	68
CLOUD POINT, C	D2500	-12	-13	-12	-14	-16	-16	-12
POUR POINT, C	D97	-14	-16	-15	-18	-17	-19	-16
K VIS @ 40 C, cSt	D445	2.75	2.76	2.75	2.76	2.77	2.76	2.53
K VIS @ 5 C, cSt	D445	6.64	6.7	6.73	6.82	6.94	6.92	5.83
AROMATICS, VOL %	D1319	29.7	42.3	45.7	48.5	48.7	51.4	30.1
AUTOIGNITION TEMP., C	E659	188	186	187	190	193	193	188
ANILINE PT, C	D611	60.5	58.6	55.5	54.4	51.6	49.2	61.9
CETANE NUMBER	D613	44.9	43.5	41.8	41.3	39.7	38.7	46.3
D2887 IBP, C	D2887	137	138	139	142	142	143	136
D2887 10% PT, C	D2887	211	212	213	214	215	216	197
D2887 20% PT, C	D2887	233	233	233	235	236	237	220
D2887 30% PT, C	D2887	248	249	250	252	253	255	238
D2887 40% PT, C	D2887	260	260	261	262	263	263	255
D2887 50% PT, C	D2887	274	274	275	276	276	277	270
D2887 60% PT, C	D2887	288	288	289	289	290	290	284
D2887 70% PT, C	D2887	305	304	304	305	306	306	302
D2887 80% PT, C	D2887	322	323	323	324	324	325	319
D2887 90% PT, C	D2887	346	347	347	348	348	348	345
D2887 99.5% PT, C	D2887	403	403	404	404	403	404	402
D86 IBP, C	D86	199	178	181	190	190	198	163
D86 10% PT, C	D86	227	224	226	226	227	230	205
D86 20% PT, C	D86	237	237	237	238	236	242	222
D86 30% PT, C	D86	246	247	246	248	245	251	235
D86 40% PT, C	D86	256	256	256	257	257	259	247
D86 50% PT, C	D86	266	265	265	267	267	268	257
D86 60% PT, C	D86	277	276	275	276	275	278	268
D86 70% PT, C	D86	288	288	287	288	288	291	281
D86 80% PT, C	D86	304	302	301	303	303	304	297
D86 90% PT, C	D86	324	321	320	323	324	324	317
D86 95% PT, C	D86	339	335	334	340	339	338	331
D86 EP, C	D86	352	349	349	353	352	355	346
D86 % RECOVERED	D86	99	99	99	99	99	99	99
D86 RESIDUE, %	D86	1	1	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	5	6	7	7	8	10	4
% MONO-AROMATIC RING H	NMR	1	1	2	2	2	1	2
% ALPHA H	NMR	7	8	9	10	10	12	7
% H ON CARBON	NMR	49	50	46	47	46	46	50
% H ON TERMINAL CARBON	NMR	35	32	34	31	31	28	35

* *Rounding off of these NMR values may result in totals other than 100%.*

PROPERTY	METHOD	14031	14032	14033	14053	14054
FUEL BLEND	BFLRF	90A/10R	85A/15R	87.5A/12.5R	75A/25R	75A/25O
SPEC. GRAVITY @ 15.6 C	D1298	0.8519	0.8524	0.8514	0.855	0.8745
API GRAVITY, DEG.	D1298	34.6	34.5	34.7	34	30.3
FLASH POINT, C	D93S6	64	59	63	55	77
CLOUD POINT, C	D2500	-15	-14	-14	-18	-14
POUR POINT, C	D97	-15	-21	-19	-21	-10
K VIS @ 40 C, cSt	D445	2.28	2.09	2.19	1.79	2.76
K VIS @ 5 C, cSt	D445	5.05	4.44	4.83	3.63	6.02
AROMATICS, VOL %	D1319	32.8	38	42	51	40.5
AUTOIGNITION TEMP., C	E659	189	186	185	192	190
ANILINE PT, C	D611	58	53.6	57.4	45.8	54.4
CETANE NUMBER	D613	43.8	41.8	44.3	37.9	41.3
D2887 IBP, C	D2887	139	139	139	140	142
D2887 10% PT, C	D2887	171	167	169	165	214
D2887 20% PT, C	D2887	210	194	205	172	235
D2887 30% PT, C	D2887	232	221	229	197	252
D2887 40% PT, C	D2887	250	241	247	227	262
D2887 50% PT, C	D2887	264	258	262	249	276
D2887 60% PT, C	D2887	280	275	278	267	289
D2887 70% PT, C	D2887	297	293	296	287	305
D2887 80% PT, C	D2887	317	314	316	308	324
D2887 90% PT, C	D2887	343	340	342	336	348
D2887 99.5% PT, C	D2887	401	401	401	398	404
D86 IBP, C	D86	167	158	167	157	190
D86 10% PT, C	D86	196	189	194	179	226
D86 20% PT, C	D86	216	202	211	190	238
D86 30% PT, C	D86	232	220	228	204	248
D86 40% PT, C	D86	245	230	244	224	257
D86 50% PT, C	D86	257	252	258	244	267
D86 60% PT, C	D86	268	265	268	260	276
D86 70% PT, C	D86	282	279	283	274	288
D86 80% PT, C	D86	298	296	298	291	303
D86 90% PT, C	D86	318	317	319	314	323
D86 95% PT, C	D86	335	331	337	333	340
D86 EP, C	D86	348	348	348	339	353
D86 % RECOVERED	D86	99	99	99	99	99
D86 RESIDUE, %	D86	1	1	1	1	1
D86 LOSS, %	D86	0	0	0	0	0
% DI-AROMATIC RING H	NMR*	5	4	3	6	7
% MONO-AROMATIC RING H	NMR	3	4	3	5	2
% ALPHA H	NMR	10	11	10	16	10
% H ON CARBON	NMR	48	45	47	44	47
% H ON TERMINAL CARBON	NMR	33	33	34	27	31

* Rounding off of these NMR values may result in totals other than 100%.

APPENDIX B

FUEL FLUSHING PROCEDURE FOR NAVY COLD STARTS

FUEL FLUSHING PROCEDURE FOR NAVY COLD STARTS

1. Remove the suction line and return line from the fuel can. Place the suction line into the can containing approximately 3 gallons of the new fuel. Place the return line into the dump can.

2. Start the engine, letting it run for 20 seconds before shutting down.

3. Change the secondary filter.

4. Start the engine and run at least 1 gallon of the new fuel through the engine. The fuel should be emptied from the engine into the dump can. After 1 gallon has been run through, shut down the engine.

5. Place both fuel lines into a smaller fuel can containing 0.75 gallons of new fuel. Start the engine and burn approximately 0.25 gallons of fuel while the engine runs at 800 to 900 rpm with an 80 ft-lb load. After 0.25 gallons has been burned, shut down the engine.

6. Zero the scale or balance on which the fuel can is sitting, seal the cold box, and cool down for the next day's test.

APPENDIX C

COLD-STARTING DATA AT 5°C

ENGINE = DDA 4-53T

OBS	DATE	AL CODE	CRANKING SPEED, RPM	START TIME, SECONDS
1	08FEB85	AL-13279-F	NA	8.2
2	11FEB85	AL-13279-F	NA	6.2
3	12FEB85	AL-13279-F	NA	6.4
4	13FEB85	AL-13279-F	NA	1.6
5	14FEB85	AL-13279-F	NA	1.6
6	15FEB85	AL-13894-F	NA	7.3
7	16FEB85	AL-13894-F	NA	16.4
8	17FEB85	AL-13894-F	NA	11.6
9	18FEB85	AL-13894-F	NA	5.4
10	19FEB85	AL-13894-F	NA	7.7
11	20FEB85	AL-13907-F	NA	22.3
12	21FEB85	AL-13907-F	NA	26.5
13	22FEB85	AL-13907-F	NA	24.0
14	23FEB85	AL-13908-F	NA	29.7
15	25FEB85	AL-13908-F	NA	23.1
16	26FEB85	AL-13908-F	NA	23.2
17	27FEB85	AL-13908-F	NA	16.7
18	28FEB85	AL-13909-F	NA	28.6
19	01MAR85	AL-13909-F	NA	29.7
20	03MAR85	AL-13909-F	NA	21.5
21	04MAR85	AL-13909-F	NA	29.0
22	05MAR85	AL-13909-F	NA	22.0
23	07MAR85	AL-13990-F	NA	9.4
24	08MAR85	AL-13990-F	NA	13.5
25	09MAR85	AL-13991-F	NA	15.8
26	10MAR85	AL-13991-F	NA	15.7
27	11MAR85	AL-13991-F	NA	17.8
28	13MAR85	AL-13992-F	NA	20.6
29	17MAR85	AL-13992-F	NA	16.7
30	18MAR85	AL-13992-F	NA	15.1
31	19MAR85	AL-13993-F	NA	17.1
32	20MAR85	AL-13993-F	NA	17.7
33	21MAR85	AL-13993-F	NA	16.4
34	22MAR85	AL-14003-F	NA	10.1
35	23MAR85	AL-14003-F	NA	4.7
36	24MAR85	AL-14003-F	NA	7.1
37	25MAR85	AL-14003-F	NA	2.1
38	26MAR85	AL-14004-F	NA	3.1
39	27MAR85	AL-14004-F	NA	6.8
40	28MAR85	AL-14004-F	NA	7.8
41	29MAR85	AL-14005-F	NA	9.0
42	30MAR85	AL-14005-F	NA	13.9
43	31MAR85	AL-14005-F	NA	9.5
44	01APR85	AL-14005-F	NA	8.2
45	02APR85	AL-14006-F	NA	12.7
46	03APR85	AL-14006-F	NA	17.4
47	04APR85	AL-14006-F	NA	23.7
48	06APR85	AL-14053-F	NA	33.1
49	07APR85	AL-14053-F	NA	31.7
50	08APR85	AL-14053-F	NA	29.8
51	10APR85	AL-14054-F	NA	17.0
52	11APR85	AL-14054-F	NA	25.3
53	12APR85	AL-14054-F	NA	24.1

ENGINE = DDA 4-71TI

OBS	DATE	AL CODE	CRANKING SPEED, RPM	START TIME, SECONDS
54	NA	AL-13279-F	230	22.0
55	NA	AL-13279-F	235	27.0
56	NA	AL-13279-F	235	40.0
57	NA	AL-13279-F	240	23.0
58	NA	AL-13279-F	230	20.0
59	NA	AL-13279-F	220	32.0
60	NA	AL-13864-F	230	40.0
61	NA	AL-13864-F	230	35.0
62	NA	AL-13864-F	235	30.0
63	NA	AL-13865-F	230	48.0
64	NA	AL-13865-F	230	36.0
65	NA	AL-13865-F	230	44.0
66	NA	AL-13865-F	250	37.0
67	NA	AL-13865-F	230	64.0
68	NA	AL-13866-F	250	65.0
69	NA	AL-13866-F	255	57.0
70	NA	AL-13866-F	250	72.0
71	NA	AL-13866-F	260	48.0
72	NA	AL-13866-F	235	75.0
73	NA	AL-13866-F	230	77.0
74	NA	AL-13867-F	260	70.0
75	NA	AL-13867-F	230	115.0
76	NA	AL-13867-F	260	150.0
77	NA	AL-13869-F	230	140.0
78	NA	AL-13869-F	270	77.0
79	NA	AL-13869-F	220	225.0
80	NA	AL-14019-F	230	31.0
81	NA	AL-14019-F	220	53.0
82	NA	AL-14019-F	230	60.0
83	NA	AL-14020-F	230	80.0
84	NA	AL-14020-F	225	69.0
85	NA	AL-14020-F	230	73.0
86	NA	AL-14020-F	230	63.0
87	NA	AL-14021-F	220	70.0
88	NA	AL-14021-F	225	94.3
89	NA	AL-14021-F	225	102.3
90	NA	AL-14021-F	210	127.0
91	NA	AL-14022-F	205	97.0
92	NA	AL-14022-F	220	87.0
93	NA	AL-14022-F	220	84.0
94	NA	AL-14023-F	210	105.0
95	NA	AL-14023-F	210	98.0
96	NA	AL-14024-F	215	163.0
97	NA	AL-14024-F	215	255.0
98	NA	AL-14025-F	205	233.0
99	NA	AL-14030-F	215	45.0
100	NA	AL-14030-F	210	28.0
101	NA	AL-14030-F	220	43.0
102	NA	AL-14031-F	210	52.0
103	NA	AL-14031-F	220	40.0
104	NA	AL-14031-F	210	87.0
105	NA	AL-14032-F	210	110.0
106	NA	AL-14032-F	210	187.0

ENGINE = DDA 4-71TI

OBS	DATE	AL CODE	CRANKING SPEED, RPM	START TIME, SECONDS
107	NA	AL-14032-F	200	210.0
108	NA	AL-14032-F	200	215.0
109	NA	AL-14033-F	200	53.0
110	NA	AL-14033-F	200	55.0
111	NA	AL-14033-F	205	74.0
112	NA	AL-14033-F	205	83.0
113	NA	AL-14033-F	200	100.0

ENGINE = CUMMINS NH220

OBS	DATE	AL CODE	CRANKING SPEED*, RPM	START TIME, SECONDS
114	23OCT84	AL-13279-F	181	26.5
115	24OCT84	AL-13279-F	198	15.7
116	25OCT84	AL-13279-F	206	8.4
117	26OCT84	AL-13279-F	232	4.0
118	29OCT84	AL-13279-F	216	8.3
119	30OCT84	AL-13279-F	218	9.0
120	31OCT84	AL-13279-F	218	5.0
121	02NOV84	AL-13279-F	NA	14.0
122	05NOV84	AL-13634-F	227	20.0
123	06NOV84	AL-13634-F	227	17.2
124	15NOV84	AL-13634-F	210	29.1
125	16NOV84	AL-13634-F	194	22.8
126	20NOV84	AL-13634-F	195	30.4
127	21NOV84	AL-13639-F	194	38.3
128	26NOV84	AL-13639-F	202	26.3
129	27NOV84	AL-13639-F	193	33.0
130	28NOV84	AL-13664-F	195	48.2
131	29NOV84	AL-13664-F	200	31.3
132	30NOV84	AL-13684-F	NA	33.6
133	01DEC84	AL-13684-F	NA	29.8
134	02DEC84	AL-13692-F	NA	29.5
135	03DEC84	AL-13692-F	190	39.3
136	04DEC84	AL-13692-F	193	35.8
137	05DEC84	AL-13694-F	190	42.0
138	06DEC84	AL-13694-F	186	39.1
139	07DEC84	AL-13699-F	196	30.3
140	08DEC84	AL-13699-F	NA	30.4
141	09DEC84	AL-13700-F	203	23.4
142	10DEC84	AL-13700-F	NA	29.6
143	11DEC84	AL-13700-F	NA	28.7
144	12DEC84	AL-13706-F	203	27.5
145	13DEC84	AL-13706-F	206	30.1
146	14DEC84	AL-13736-F	NA	27.9
147	15DEC84	AL-13736-F	NA	27.6
148	16DEC84	AL-13737-F	NA	28.3
149	17DEC84	AL-13737-F	NA	26.6
150	18DEC84	AL-13737-F	NA	25.3
151	19DEC84	AL-13803-F	208	21.5
152	20DEC84	AL-13803-F	NA	19.6
153	21DEC84	AL-13803-F	206	21.8
154	22DEC84	AL-13850-F	202	35.7
155	23DEC84	AL-13850-F	201	32.9

* Cranking speeds shown are computer-derived averages as described in the text. Speeds for other engines in this appendix are operator-read.

ENGINE = WESTERBEKE 4-108

OBS	DATE	AL CODE	CRANKING SPEED, RPM	START TIME, SECONDS
156	NA	AL-13279-F	250	11.5
157	NA	AL-13279-F	255	13.0
158	NA	AL-13279-F	300	4.0
159	NA	AL-13279-F	240	17.0
160	NA	AL-13279-F	260	6.0
161	NA	AL-13279-F	290	17.5
162	NA	AL-13279-F	290	5.0
163	NA	AL-13279-F	270	8.0
164	NA	AL-13864-F	250	15.0
165	NA	AL-13864-F	300	3.0
166	NA	AL-13864-F	280	4.0
167	NA	AL-13865-F	240	10.5
168	NA	AL-13865-F	280	10.0
169	NA	AL-13865-F	225	9.0
170	NA	AL-13865-F	290	8.0
171	NA	AL-13866-F	250	11.0
172	NA	AL-13866-F	250	15.0
173	NA	AL-13866-F	250	22.0
174	NA	AL-13866-F	230	10.0
175	NA	AL-13866-F	225	13.0
176	NA	AL-13867-F	230	18.0
177	NA	AL-13867-F	240	15.0
178	NA	AL-13867-F	300	10.0
179	NA	AL-13868-F	250	33.0
180	NA	AL-13868-F	240	45.0
181	NA	AL-13868-F	220	48.0
182	NA	AL-13868-F	280	24.0
183	NA	AL-13869-F	240	22.0
184	NA	AL-13869-F	250	17.0
185	NA	AL-13869-F	250	20.0
186	NA	AL-13870-F	270	49.0
187	NA	AL-13870-F	280	50.0
188	NA	AL-13870-F	260	47.0
189	NA	AL-13871-F	240	52.0
190	NA	AL-13871-F	270	34.0
191	NA	AL-13871-F	270	27.0
192	NA	AL-13871-F	260	41.0
193	NA	AL-14019-F	200	18.0
194	NA	AL-14019-F	220	20.0
195	NA	AL-14019-F	240	11.0
196	NA	AL-14020-F	220	15.0
197	NA	AL-14020-F	225	18.0
198	NA	AL-14020-F	200	30.0

ENGINE = WESTERBEKE 4-108

OBS	DATE	AL CODE	CRANKING SPEED, RPM	START TIME, SECONDS
199	NA	AL-14021-F	200	19.0
200	NA	AL-14021-F	225	30.5
201	NA	AL-14021-F	225	28.5
202	NA	AL-14022-F	225	39.0
203	NA	AL-14022-F	225	40.0
204	NA	AL-14022-F	220	45.0
205	NA	AL-14023-F	220	51.0
206	NA	AL-14023-F	200	55.0
207	NA	AL-14023-F	200	90.0
208	NA	AL-14024-F	210	22.0
209	NA	AL-14024-F	230	24.0
210	NA	AL-14025-F	210	124.0
211	NA	AL-14025-F	220	114.0
212	NA	AL-14030-F	210	27.0
213	NA	AL-14030-F	240	17.0
214	NA	AL-14030-F	230	17.0
215	NA	AL-14031-F	220	26.0
216	NA	AL-14031-F	200	44.0
217	NA	AL-14032-F	210	28.0
218	NA	AL-14032-F	200	87.0
219	NA	AL-14032-F	190	150.0
220	NA	AL-14032-F	200	53.0
221	NA	AL-14033-F	210	15.0
222	NA	AL-14033-F	210	43.0
223	NA	AL-14033-F	230	26.0
224	NA	AL-14033-F	220	27.0
225	NA	AL-14033-F	230	8.0

APPENDIX D

PAIRWISE CROSS-CORRELATION MATRICES

TABLE D-1. Pairwise Correlation Coefficients for DDA 4-53T Engine

	Speed	Specific Gravity	Flash Point	Cloud Point	Pour Point	K. Vis. at 40°C	D 301	D 701	Aniline Point	Mono-aromatics	Di-aromatics	Tri-aromatics	Auto-ignition	Freeze Point	New Cetane
Speed	1.00000	-0.00064	0.01346	-0.10033	-0.05805	-0.04018	-0.05187	0.05455	-0.07764	0.00274	-0.06462	-0.12067	0.23495	-0.16860	-0.05326
Specific Gravity	-0.00064	1.00000	0.33687	0.08757	0.00050	0.27004	0.33775	0.15790	-0.34165	-0.19071	0.90094	0.80344	0.02339	0.33696	-0.42002
Flash Point	0.01346	0.33687	1.00000	0.65373	0.64040	0.95796	0.95185	0.73063	0.80441	-0.90031	0.62471	0.60011	-0.25625	0.74500	0.65440
Cloud Point	-0.10033	0.08757	0.65373	1.00000	0.75007	0.80184	0.78253	0.37383	0.76688	-0.85590	0.44025	0.55268	-0.27001	0.68537	0.69058
Pour Point	-0.05805	0.00050	0.64040	0.75007	1.00000	0.78500	0.75346	0.63160	0.72706	-0.82457	0.43048	0.54699	-0.16009	0.61338	0.60096
K. Vis. at 40°C	-0.04018	0.27004	0.95796	0.80184	0.78500	1.00000	0.97613	0.72246	0.79825	-0.90640	0.62958	0.66957	-0.22657	0.83371	0.73888
D 301	-0.05187	0.33775	0.95185	0.78253	0.75346	0.97613	1.00000	0.74366	0.74714	-0.96461	0.66561	0.68040	-0.26236	0.82943	0.80195
D 701	0.05455	0.15790	0.73063	0.37383	0.63160	0.72246	0.74356	1.00000	0.59203	-0.60218	0.39088	0.38776	-0.23164	0.59634	0.50027
Aniline Point	-0.07764	-0.34165	0.80441	0.76688	0.72706	0.79825	0.74714	0.59203	1.00000	-0.85443	0.07170	0.19504	-0.22599	0.64899	0.98367
Mono-aromatics	0.00274	-0.19071	-0.90031	-0.85590	-0.82457	-0.90640	-0.96461	-0.60218	-0.85443	1.00000	-0.57232	-0.64021	0.23384	-0.85416	-0.79663
Di-aromatics	-0.06462	0.90094	0.62471	0.44025	0.43048	0.62958	0.66561	0.39088	0.07170	-0.57232	1.00000	0.96374	-0.04807	0.65225	-0.03313
Tri-aromatics	-0.12067	0.80344	0.60011	0.55268	0.54699	0.66957	0.68040	0.38776	0.19504	-0.64021	0.96374	1.00000	-0.03003	0.75201	0.08481
Autoignition	0.23495	0.02339	-0.25625	-0.27001	-0.16009	-0.22657	-0.26236	-0.23164	-0.22599	0.23384	-0.04807	-0.03003	1.00000	-0.05349	-0.21297
Freeze Point	-0.16860	0.33696	0.74500	0.68537	0.61338	0.83371	0.82943	0.59634	0.64899	-0.85416	0.65225	0.75201	-0.05349	1.00000	0.58489
New Cetane	-0.05326	-0.42002	0.65440	0.69058	0.60096	0.73888	0.80195	0.50027	0.98367	-0.79663	-0.03313	0.08481	-0.21297	0.58489	1.00000

TABLE D-2. Pairwise Correlation Coefficients for DDA 4-71TI Engine

	Speed	Specific Gravity	Flash Point	Cloud Point	Pour Point	K. Vis. at 40°C	D 301	D 701	Aniline Point	Mono-aromatics	Di-aromatics	Tri-aromatics	Auto-ignition	Freeze Point	New Cetane
Speed	1.00000	-0.11223	0.43257	-0.26355	-0.06827	0.16081	0.07006	-0.26057	0.09262	-0.01727	-0.16320	-0.28469	0.06789	-0.24193	0.18429
Specific Gravity	-0.11223	1.00000	0.45907	-0.16614	0.03207	0.39540	0.55178	0.27794	-0.58115	-0.24370	0.95295	0.85509	0.46451	0.56929	-0.69958
Flash Point	0.43257	0.45907	1.00000	0.17466	0.45208	0.90621	0.87315	0.56175	0.28397	-0.77225	0.58852	0.56134	0.31393	0.54329	0.20970
Cloud Point	-0.26355	-0.16614	0.17466	1.00000	0.53545	0.39464	0.30306	0.53062	0.55553	-0.49442	0.01812	0.15440	-0.30949	0.07166	0.46302
Pour Point	-0.06827	0.03207	0.45208	0.53545	1.00000	0.70115	0.66837	0.78272	0.62468	-0.79140	0.26220	0.41332	0.01525	0.39514	0.52954
K. Vis. at 40°C	0.16081	0.39540	0.90621	0.39464	0.70115	1.00000	0.97113	0.84942	0.49473	-0.96247	0.61690	0.68649	0.31810	0.70302	0.36572
D 301	0.07006	0.55178	0.87315	0.30306	0.66837	0.97113	1.00000	0.85213	0.34431	-0.92593	0.75379	0.81241	0.41365	0.78117	0.20117
D 701	-0.26057	0.27794	0.56175	0.53062	0.78272	0.84942	0.85213	1.00000	0.56813	-0.94099	0.55008	0.72437	0.27167	0.78298	0.40294
Aniline Point	0.09262	-0.58115	0.28397	0.55553	0.62468	0.49473	0.34431	0.56813	1.00000	-0.64208	-0.31948	-0.13247	-0.12678	0.15992	0.96990
Mono-aromatics	-0.01727	-0.24370	-0.77225	-0.49442	-0.79140	-0.96247	-0.92593	-0.94099	-0.64208	1.00000	-0.51048	-0.64447	-0.26033	-0.71201	-0.50659
Di-aromatics	-0.16320	0.95295	0.58852	0.01812	0.26220	0.61690	0.75379	0.55008	-0.31948	-0.51048	1.00000	0.96609	0.49248	0.73387	-0.47587
Tri-aromatics	-0.28469	0.85509	0.56134	0.15440	0.41332	0.68649	0.81241	0.72437	-0.13247	-0.64447	0.96609	1.00000	0.47429	0.82972	-0.30690
Autoignition	0.06789	0.46451	0.31393	-0.30949	0.01525	0.31810	0.41365	0.27167	-0.12678	-0.26033	0.49248	0.47429	1.00000	0.60723	-0.19295
Freeze Point	-0.24193	0.56929	0.54329	0.07166	0.39514	0.70302	0.78117	0.78298	0.15992	-0.71201	0.73387	0.82972	0.60723	1.00000	0.01857
New Cetane	0.18429	-0.69958	0.20970	0.46302	0.52954	0.36572	0.20117	0.40294	0.96990	-0.50659	-0.47587	-0.30690	-0.19295	0.01857	1.00000

TABLE D-3. Pairwise Correlation Coefficients for Westerbeke 4-108 Engine

	Speed	Specific Gravity	Flash Point	Cloud Point	Pour Point	K. Vis. at 40°C	D 301	D 701	Aniline Point	Mono-aromatics	Di-aromatics	Tri-aromatics	Auto-ignition	Freeze Point	New Cetane
Speed	1.00000	0.20071	0.16507	0.12679	0.22930	-0.03254	-0.12276	-0.12279	-0.00604	0.14812	-0.30881	-0.40405	0.01732	-0.05204	0.10299
Specific Gravity	-0.20071	1.00000	0.25191	-0.36600	0.23602	0.12054	0.27743	-0.11712	-0.62326	0.09437	0.00542	0.63246	0.53877	0.55319	-0.72280
Flash Point	0.16507	0.25191	1.00000	0.27966	0.52240	0.87620	0.85062	0.00993	0.43107	-0.72109	0.51002	0.58339	0.26550	0.54472	0.36370
Cloud Point	-0.12679	0.36600	0.27966	1.00000	0.65500	0.49658	0.40594	0.07927	0.68044	-0.59675	-0.07417	0.20411	-0.28900	0.02412	0.63822
Pour Point	0.22930	0.23602	0.52240	0.65500	1.00000	0.00033	0.75726	0.47014	0.82981	-0.90173	0.17191	0.51212	-0.00249	0.19523	0.76509
K. Vis. at 40°C	-0.03254	0.12054	0.87620	0.49658	0.00033	1.00000	0.97652	0.37666	0.67275	-0.94710	0.51226	0.72915	0.25326	0.56736	0.58712
D 301	-0.12276	0.27743	0.85062	0.40594	0.75726	0.97652	1.00000	0.37402	0.56353	-0.91445	0.65381	0.84072	0.34769	0.64527	0.45754
D 701	-0.12279	-0.11712	0.00993	0.07927	0.47014	0.37666	0.37402	1.00000	0.41367	-0.48298	0.11156	0.30943	-0.01786	-0.00155	0.40052
Aniline Point	0.00604	0.62326	0.43107	0.68044	0.82981	0.67275	0.56353	0.41367	1.00000	-0.83383	-0.21716	0.18137	-0.19929	0.04177	0.97876
Mono-aromatics	0.14812	0.09437	0.72100	-0.59675	0.90173	-0.94710	-0.91445	-0.48298	-0.83383	1.00000	-0.34955	-0.67236	-0.11765	-0.43337	-0.74645
Di-aromatics	0.30881	0.00542	0.51002	-0.07417	0.17191	0.51226	0.65381	0.11156	-0.21716	-0.34955	1.00000	0.90599	0.56109	0.71928	-0.35630
Tri-aromatics	-0.40405	0.63246	0.58339	0.20411	0.51212	0.72915	0.84072	0.30943	0.18137	-0.67236	0.90599	1.00000	0.45452	0.72431	0.02567
Autoignition	0.01732	0.53877	0.26550	-0.28900	0.00249	0.25326	0.34769	-0.01786	-0.19929	-0.11765	0.56109	0.45452	1.00000	0.62947	-0.24295
Freeze Point	-0.05204	0.55319	0.54472	0.02412	0.19523	0.56736	0.64527	-0.00155	0.04177	-0.43337	0.71928	0.72431	0.62947	1.00000	-0.05292
New Cetane	0.10299	-0.72280	0.36370	0.63822	0.76509	0.58712	0.45754	0.40052	0.97876	-0.74645	-0.35630	0.02567	-0.24295	-0.05292	1.00000

TABLE D-4. Pairwise Correlation Coefficients for Cummins NH-220 Engine

	Speed	Specific Gravity	Flash Point	Cloud Point	Pour Point	K. Vis. at 40°C	D 301	D 701	Aniline Point	Mono-aromatics	Di-aromatics	Tri-aromatics	Auto-ignition	Freeze Point	New Cetane
Speed	1.00000	-0.50885	0.03787	0.14332	-0.12704	0.07607	0.00539	0.04083	0.32044	-0.10496	-0.43727	-0.30258	0.16132	0.29782	0.30132
Specific Gravity	-0.50885	1.00000	0.00994	-0.20084	0.13572	-0.14936	-0.06573	-0.03573	-0.63767	0.25939	0.75275	0.42129	-0.31047	-0.66762	-0.66095
Flash Point	0.03787	0.00994	1.00000	0.15400	0.57066	0.89451	0.89033	0.80732	0.62675	-0.81876	0.45591	0.51467	0.23010	0.63413	0.64862
Cloud Point	0.14332	-0.20084	0.15400	1.00000	0.56011	0.46541	0.43115	0.24394	0.59000	-0.55828	0.17434	0.46321	0.23833	0.44984	0.47859
Pour Point	-0.12704	0.13572	0.57066	0.56011	1.00000	0.78106	0.77649	0.70970	0.55583	-0.76257	0.60427	0.70841	0.00041	0.39189	0.49836
K. Vis. at 40°C	0.07607	-0.14936	0.89451	0.46541	0.78106	1.00000	0.98645	0.84757	0.84240	-0.98262	0.46460	0.66197	0.29134	0.77005	0.82009
D 301	0.00539	-0.06573	0.89033	0.43115	0.77649	0.98645	1.00000	0.84847	0.79128	-0.97082	0.55142	0.73278	0.35473	0.74339	0.78321
D 701	0.04083	-0.03573	0.80732	0.24394	0.70970	0.84757	0.84847	1.00000	0.63003	-0.78280	0.37420	0.44370	0.24129	0.53882	0.66274
Aniline Point	0.32044	-0.63767	0.62675	0.59000	0.55583	0.84240	0.79128	0.63003	1.00000	-0.90378	-0.00465	0.34807	0.42490	0.93932	0.97337
Mono-aromatics	-0.10496	0.25939	-0.81876	-0.55828	-0.76257	-0.98262	-0.97082	-0.78280	-0.90378	1.00000	-0.40497	-0.66783	-0.35626	-0.84046	-0.87941
Di-aromatics	-0.43727	0.75275	0.45591	0.17434	0.60427	0.46460	0.55142	0.37420	-0.00465	-0.40497	1.00000	0.90404	0.01250	-0.06125	-0.05388
Tri-aromatics	-0.30258	0.42129	0.51467	0.46321	0.70841	0.66197	0.73278	0.44370	0.34807	-0.66783	0.90404	1.00000	0.18364	0.28759	0.29000
Autoignition	0.16132	-0.31047	0.23010	0.23833	0.00041	0.29134	0.35473	0.24129	0.42490	-0.35626	0.01250	0.18364	1.00000	0.54327	0.44876
Freeze Point	0.29782	-0.66762	0.63413	0.44984	0.39189	0.77005	0.74339	0.53882	0.93932	-0.84046	-0.06125	0.28759	0.54327	1.00000	0.97035
New Cetane	0.30132	-0.66095	0.64862	0.47859	0.49836	0.82009	0.78321	0.66274	0.97337	-0.87941	-0.05388	0.29000	0.44876	0.97035	1.00000

APPENDIX E

ENGINE SPECIFICATION AND REBUILD PARTS

Engine Specifications

	DDA 4-53T	Cummins NH220G
Model	5047-5340	NH220G
Operating Cycles	2	4
Configuration	Turbo-Supercharged	Normally Aspirated
No. Cylinders	4-Inline	6-Inline
Injection	Direct, DDA Unit Injectors	Direct, Cummins PT
Bore, in. (mm)	3.875 (98)	5.125 (130)
Stroke, in. (mm)	4.5 (114)	6.0 (152)
Displacement, in.^{3} (ℓ)	212 (3.48)	743 (12.18)
Torque, lb-ft at RPM (Nm)	402 at 1800 (545)	554 at 1800 (751)
Power, bhp at RPM (kW)	170 at 2500 (127)	190 at 1800 (142)
Compression Ratio	18.7:1	15.8:1

	Westerbeke 4-108	DDA 4-71TI
Model	14088	1043-7303
Operating Cycles	4	2
Configuration	Normally Aspirated	Turbocharged-Intercooled
No. Cylinders	4-Inline	4-Inline
Injection	Indirect	Direct, DDA Unit Injectors
Bore, in. (mm)	3.125 (79.37)	4.25 (108)
Stroke, in. (mm)	3.5 (88.9)	5.0 (127)
Displacement, in.^{3} (ℓ)	107.4 (1.76)	284 (4.66)
Torque, lb-ft at RPM (Nm)	79 (109)	NA
Power, bhp at RPM (kW)	37 at 3000 (28)	300 at 2500 (544)
Compression Ratio	22:1	17:1

Replacement Parts Used in the Rebuild of Test Engines

Description	4-53T	NH220	4-108	4-71TI
Piston-Liner-Ring Kit	5149734	AR7383	NU*	NU
Piston	NU	NU	19938	5149983
Liner	NU	NU	19990	5197565
Ring Set	NU	NU	19937	5199824
Camshaft	NU	NU	12605	5149391
Rod Bearing	5149452	203670	NA**	NA
Main Bearing Set	5149447	3801260	NA	NA
Connecting Rod	5108178	NU	19935	5144847
Injector	5228900	BM68974XX	11701	J&T Super M95
Fuel Injection Pump	None	NH220C512822	DPA 14678	NA
Blower	NA	None	NA	5138557
Turbocharger	5103905	None	None	5143110
Exhaust Manifold	NU	NU	12411	5163809
Injection Timing	1.460	Dial Indic.	NA	1.460
Gear Train Timing	To Mark	To Mark	NA	Advance
Throttle Delay	None	None	NA	Piston Type
Gasket Set, Complete	5199792	NU	NA	NA
Pan Gasket Set	NU	3801466	NA	NA
Head Gsket Set	NU	3802077	NA	NA

*NU = Not Used
**NA = Not Available

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